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PERFORMANCE OF EXPANDED POLYMER CUSHION MATERIALS AT LESS THAN ONE INCH IN THICKNESS

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by
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Accepted by:
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ABSTRACT:

The purpose of this work is to determine whether peak acceleration values can be predicted from existing cushion curves for polymeric materials with thicknesses less than one inch. The secondary purpose is to determine whether the stress energy method of cushion testing can be applied to polymeric foams with thicknesses less than one inch. Cushion curves were created from materials greater than one inch in thickness and from materials less than one inch in thickness. The curves were compared using three methods; linear regression, comparison of cushion curves by ASTM allowable difference between curves and comparison of predicted acceleration values to actual recorded acceleration values. The curves were found to be statistically different from each other using linear regression. The curves were also found to be different according to ASTM methods of comparing cushion curves. Finally, the predicted acceleration values were significantly different that the actual recorded acceleration values.

ACKNOWLEDGEMENTS:

I would like to thank my wife and family for their encouragement, the Packaging Science Department of Clemson University for their support and Nova Chemicals, Inc. for their knowledge, materials and funding. I would not have been able to complete this project without the combined effort of those involved.

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CHAPTER ONE

INTRODUCTION:

Cushion curves are a valuable tool used by packaging engineers when developing protective packaging systems. These curves are used to predict the level of acceleration that the product will experience when dropped from a particular drop height. The curves are specific to the material density, thickness of the cushion and the drop height. The cushion curves that exist now provide acceleration values for materials with a minimum thickness of one inch. Any packaging engineer wanting to design with foams less than one inch in thickness must use trial and error when designing the package system. The purpose of this study is to determine if cushion curves created from foams thicker than one inch can be used to predict acceleration values from foams less than one inch in thickness. Curves for material less than one inch in thickness would allow packaging designers to accurately design package systems utilizing material less than one inch in thickness.

According to the New York Times, as of 2009, 37% of all manufactured goods sold in America were imported. This is almost double the percentage of imported goods sold in 1991 (Uchitelle, 2009). Because of this trend in manufacturing and the costs of shipping associated with it, package designers must design package systems that optimize the cube efficiency. This optimization is forcing package designers to consider cushion thicknesses less than one inch. Some of these designs result in better container cube utilization, which reduces the overall cost of shipping by reducing the number of shipments used.

This reduction in material thickness and number of shipments required to move the same amount of manufactured goods also has environmental benefits. Better cube optimization would result in fewer shipments of manufactured goods. Also, less material could be used in packaging, resulting in less material in land fills.

CHAPTER TWO

LITERATURE REVIEW:

Common Transport Hazards:

Most products must go through some form of a distribution cycle. This can range from a small trip to overseas travel. The product can see only one form of transportation or it may see many forms, such as sea, rail and truck. During distribution, the product is subjected to many forms of hazards. The three most common are vibration, compression and shock.

Vibration is defined according to Harris and Crede (1987) as oscillation in a mechanical system. The specific vibration is defined by its frequency (or frequencies) and amplitude. Vibrations may be classified as either ‘periodic’ or ‘complex’. Periodic vibrations repeat themselves at a specific interval of time. If there is no repetition then the frequency is classified as complex. Vibrations may also be defined as ‘deterministic’ or ‘random’. If the future value of the vibration can be predicted, it is deterministic, if the value cannot be predicted it is random. Most vibrations experienced by a packaged product are random and complex in nature.

Vibration in distribution is often modeled as a spring, a mass and a damper. Blake (1987) describes the three components in the model: the spring as a means of storing potential energy, the mass as a means of storing kinetic energy and the damper as the means by which energy is gradually lost. He further describes the vibration of a system as “involving the alternating transfer of energy between its potential and kinetic forms. In a damped system, some energy is dissipated at each cycle of vibration and must be replaced from an external source if a steady vibration is to be maintained.”

The vibration model can be either ‘free’ or ‘forced’. A model that describes free vibration has a single moment of energy imparted in it and is allowed to vibrate without any other influences. A forced vibration system has a continual amount of energy being imparted into the system.

Vibration is seen in all forms of distribution. The main source of vertical vibrations in the trucking industry is from uneven pavement. The unevenness of the pavement is random, and so the nature of the vibrations is also random.

According to Silva (2005), “shock occurs when a force, a position, a velocity, or an acceleration is abruptly modified and creates a transient state in the system considered.” Shock is further defined by Silva (2005) “as a vibratory excitation having a duration between the natural period of the excited mechanical system and the two times that period.”

Shocks may be classified as simple or “perfect” shocks if they can be represented by a single mathematical equation (Silva 2005). These simple shocks fall into three categories; half-sine, rectangular and terminal peak saw-tooth. Figure 1 shows the three different perfect shocks.

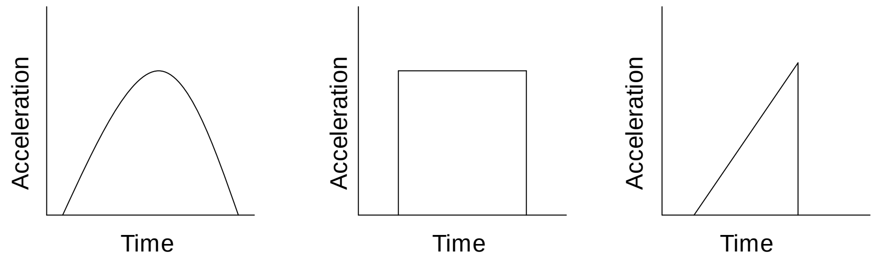


Figure 1: Example of three simple shocks; half-sine, rectangle and terminal peak saw-tooth

Shock in packaging is often seen during the distribution environment from drops, (a package falling from a height onto a surface), impacts, (an object falling onto a package), and side kicks, (horizontal shocks generally occurring from packages sliding during truck transport). Shocks seen in transportation by truck may happen due to the truck hitting potholes, running over curbs or railroad tracks and packages sliding during transportation (Soroka, 2002).

Compression is the final threat to a product in the distribution environment. Compression can be defined as the reduction in volume of a given object. In packaging there are two main types of compression, static compression and dynamic compression. Static compression occurs when a load is placed on the subject and then allowed to compress. Static compression generally occurs during the storage of a product in a warehouse environment. Dynamic compression occurs when a load is placed on the subject and then they are both moved. Dynamic compression is seen in the back of trucks during shipment. The package at the bottom of the truck is undergoing dynamic compression as the boxes are all being subjected to the shocks and vibration of over-the-road travel.

Cushion Foams:

Cushioning materials are used to slow down the impact from a shock. Every impact has a certain amount of energy. This energy is directly correlated to the change in velocity, known as Velocity Change (ΔV). This velocity change is the area under the curve in an acceleration vs. time graph, Figure 2. If an item is dropped onto a surface with no cushioning, the duration of the shock pulse would be very short, and the resulting deceleration would be very large. If the item had some form of cushioning, the cushion would slow down the shock pulse, thus increasing the duration of the impact, resulting in a lower acceleration value. The areas under both of the curves, ΔV, remains the same in both falls (Soroka 2002).

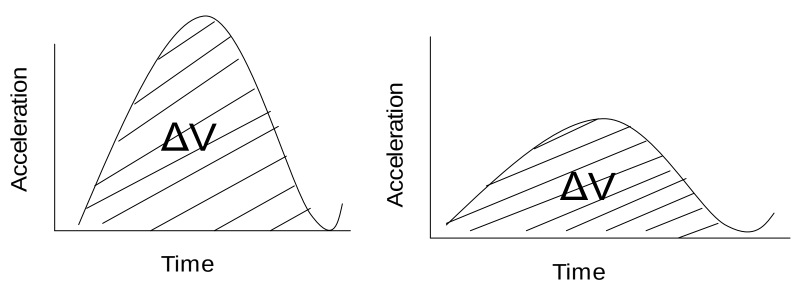


Figure 2: Example of Acceleration vs. Time curves

Foam cushions are made of thousands of small pockets of air called cells. The properties of a specific foam are dependent upon the cell structure of the foam, density of the foam, cell size distribution within the foam, and inherent polymer properties. Each of these four elements plays a role in determining the final properties of the foam. According to Lee (2007), “the properties of the gas/polymer composite often volumetrically depend on the participating components”. Density is one such example of how this relationship can work. Changes in density result in changes in mechanical properties of the final expanded foam. In general Lee states that “gas possesses minimum strength.” As such, the more gas in the foam, the lower the density and the lower the mechanical properties of the foam.

Foams belong to one of two main types, either open-cell or closed-cell foams. Both types of foams have distinct properties unique to themselves. Open-cell foams have a structure such that all of the cells, or air pockets, are connected. This gives the foam the ability to absorb moisture, enable sound proofing, allow quick gas exchanges and to improve the ability to bond to dissimilar coatings. However, compared to closed-cell foams, open-cell foams have lower insulation abilities, lower mechanical properties, such as shock absorption and a rough, uneven surface in appearance. Closed-cell foams have the opposite attributes of open-cell foams, i.e. they have higher mechanical qualities and insulative properties, but poorer water absorption and sound proofing qualities. Closed-cell foams are made of a network of cells that are not interconnected, but each cell is its own bubble. They are connected by their cell walls. Closed-cell foams are often chosen for packaging applications because of their better cushioning properties. (Lee, 2007)

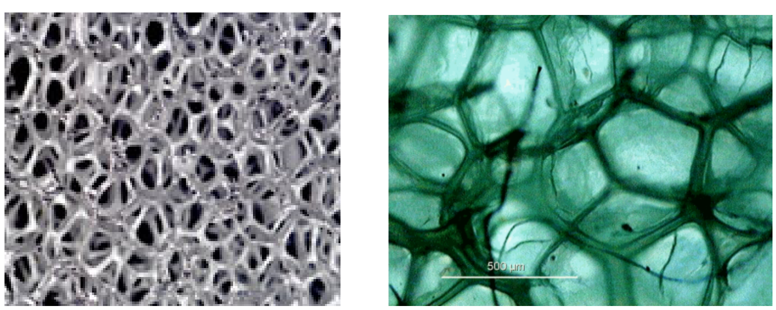


Figure 3: Open cell foam and closed cell foam (Reprinted with permission from Polymer Processing Institute 2008)

Another factor that affects properties of foam is foam density. Foams can range from extremely soft, spongy material, to one that is extremely hard. This versatility of foam makes it a valuable material for many markets. The density of foam can be calculated according to the following equation:

$$\rho = \frac{W_g + W_p}{V_g + V_p} \qquad \text{Equation 1}$$

where ρ represents density, W_g represents the weight of the gas, W_p represents the weight of the polymer, V_g represents the volume of the gas, and V_p represents the volume of the polymer. Since the weight of gas and the volume of the polymer are both typically small, foam density is largely determined from the weight of the polymer and the volume of the gas. (Lee, 2007)

Mechanical properties can be predicted based on the density and cell structure of the foam. The gas portion of the foam possesses very little strength, so as gas volume increases, strength decreases. Increasing gas volume also means that density is decreasing, so in general, a foam with low density has lower mechanical properties.

The amount of gas present in the foam also affects physical properties. An important aspect of gas in foam is to act as an energy dissipater. The gas works extremely well at absorbing the shock of impulse. This function of foam makes it extremely useful in packaging as a cushioning material designed to protect against shock. Foams also make good insulation material because the gas in the foam is poor conductor of heat. This ability of foam to act as an insulator can measured as a ‘R-value’. In general, as density decreases, meaning an increase in the gaseous volume, the R-value increases Lee (2007).

Cell size distribution, the allocation of multiple sized cells, also plays a significant role in physical properties, especially thermal properties. As the cells become smaller it requires more cells to occupy the same volume. Therefore, there are more cells present in the foam. This makes it increasingly more difficult for heat energy to transfer via conduction through the polymeric portion of foam, forcing it through the gaseous cell portions.

Compression properties of foams can be described according to their stress-strain curves, Figure 4. The curve may be split up into three distinct regions. Region 1 exhibits Hookian behavior. That is to say, the cushions exhibit linear elastic behavior which is controlled by cell wall bending in open cell foams, and by cell wall stretching in closed cell foams. Region 2 contains the collapse plateau, where cells in the foam collapse through cell wall buckling. Region 3 is where densification takes place. The material continues to experience the collapsing and crushing of impact and as such, becomes more and more dense. (Eaves 2004).

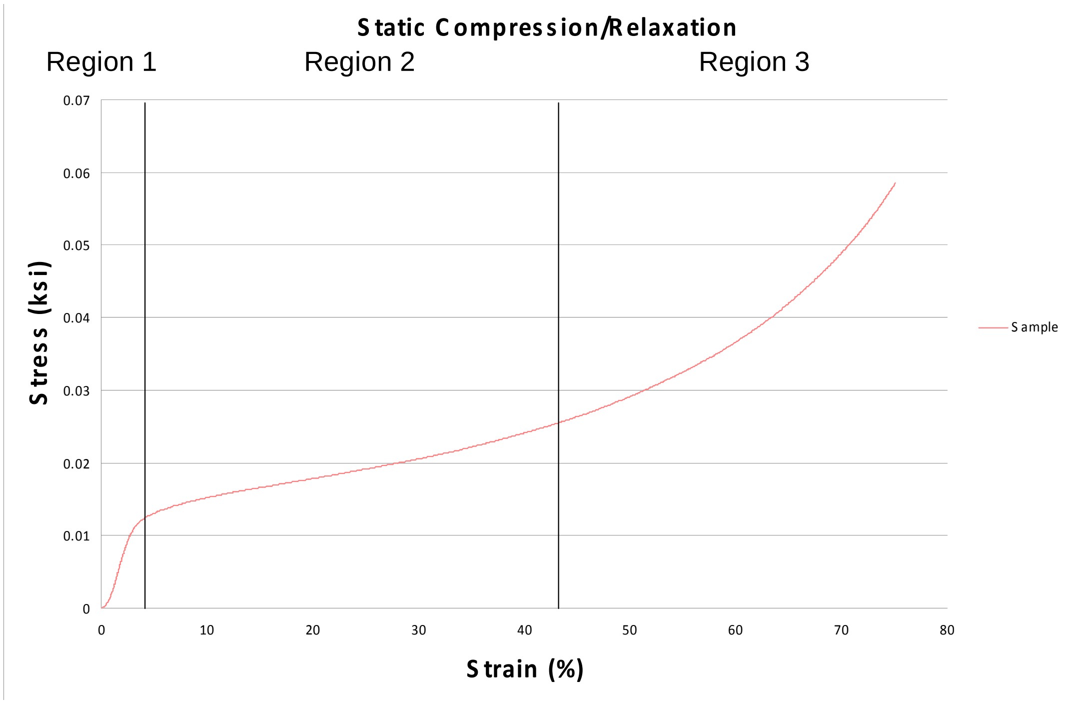


Figure 4: Example of Stress-Strain curve

Cushion Testing:

Methods to determine the effectiveness of cushioning material were developed by ASTM in 1956. The test standards, D 1596, “Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material” and D 4168, “Standard Test Method for Transmitted Shock Characteristics of Foam-in-Place Cushioning Materials” are used today by industry to characterize the cushioning ability of different polymeric foams. These standards are used to obtain what are called “Dynamic Cushion Curves”. These curves are defined by ASTM as “a graphic representation of dynamic shock cushioning or transmitted shock (in G’s) over a variety of static loading conditions (lb/in^2 or kg/m^2) for a specific cushioning material thickness (or structure) at a specific equivalent free fall drop height”. The static loading is calculated by taking the weight of the product and dividing it by the (load) bearing area of the cushioning material beneath it. What this definition means is that curves created by this standard are read as Acceleration vs. Static Load and are used only for specific thicknesses at specific heights. Figure 5 is an example of a Cushion Curve created using ASTM D 1596.

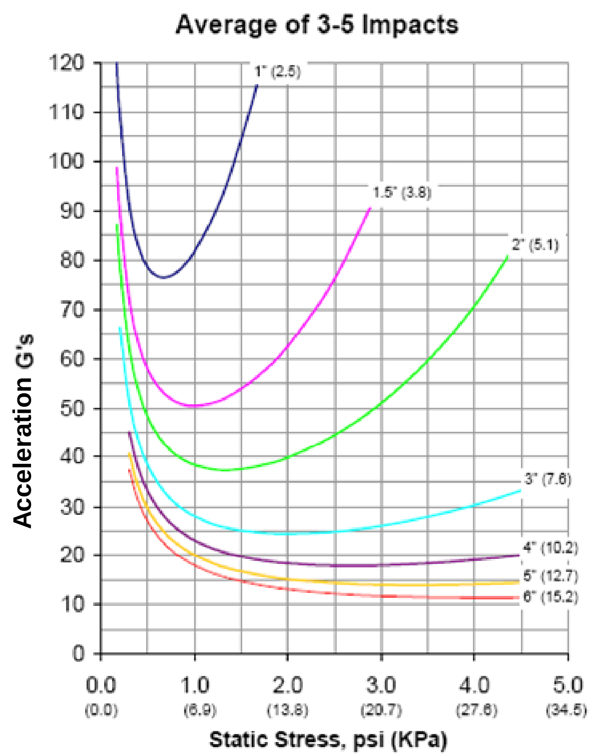


Figure 5: A typical Cushion Curve (Nova Chemical 2007)

Cushion curves are utilized by packaging engineers to determine the peak acceleration levels that a cushion will absorb. Each curve is dependent upon a specific drop height. The drop height is used to determine which set of curves will be used to determine ideal cushion thickness. The drop height is determined by predicting the types of drops that the package is likely to encounter during the distribution cycle. The engineer must also know the fragility of the product that is to be packaged. The commonly used measure of fragility is known as the critical acceleration. Critical acceleration is the maximum change in acceleration that the product can survive. The engineer then interprets the cushion curve by comparing the critical acceleration value with the suggested cushion thickness and static loads.

This method has been used for the past 50 years to develop packages to protect products throughout the distribution environment and to attempt to prevent over-packaging. Overpackaging is generally defined by using too much material for a given application.

However, there are some major drawbacks to the ASTM D 1596 method. The first is that curves are extrinsic for each material. This means that the curves are only applicable to “a specific cushioning material thickness” and at “a specific equivalent free fall drop height” (ASTM 2003). These two conditions confine the package designers to a limited amount of knowledge of the cushioning material. This makes the engineer either ‘round’ his or her estimates or to pick a cushion thickness that is greater than what he or she potentially needs.

Another problem faced by packaging designers using cushioning material is the large amount of time needed to create the curves using ASTM D 1596. According to Daum (2006), it would take over 10,500 drops and 175 hours to create a full set of curves for a single material.

Given these two main issues, another form of cushion testing/characterizing was developed by Burgess from Michigan State University. His early work with cushioning laid the groundwork for the Stress-Energy method used is this work. His initial work, in 1990, consolidated existing cushioning data into one stress-strain curve. This work showed that stress is a function of strain and strain rate, but the amount of energy needed to increase the strain rate was so high, that stress could be handled as a function of strain only. Another valuable piece of information from this early work is the realization that the amount of energy absorbed per unit volume of cushioning material is equal to the area under the stress-strain curve for that particular material and density. This showed that the cushioning ability of a material is an intrinsic property of the material itself, and as such, the acceleration values for any given drop height onto any given piece of cushion could be predicted regardless of drop height or cushion geometry. (Burgess 1990)

From this early work, Burgess proposed that a new method using less drops could be created by looking at the amount of energy a cushion could absorb based on the dynamic stress of that cushion. Dynamic stress, σ can be predicted as some function of strain, ε and strain rate, $\frac{d\varepsilon}{dt}$ in Equation 2. This method is basis for the stress-energy method.

$$\sigma = funct\left(\varepsilon, \frac{d\varepsilon}{dt}\right) \qquad \text{Equation 2}$$

The stress energy method looks at the cushioning ability of the foam as an intrinsic material property instead of a sample property. This model plots dynamic stress, DS (Equation 3) vs. dynamic energy, DE (Equation 4). The relationship linking these two variables together for closed cell polymeric foams is in Equation 5. In this equation y is dynamic stress, DS, x is dynamic energy, DE. The ‘a’ and ‘b’ coefficients are unitless coefficients defined by fitting an exponential curve to the cushion test data for a specific material (Daum, 2006).

$$DE = \frac{sh}{t} \qquad \text{Equation 3}$$

$$DS = Gs \qquad \text{Equation 4}$$

$$y = ae^{bx} \qquad \text{Equation 5}$$

Once a and b have been calculated from the dynamic stress vs. dynamic energy curve, the equations can be rearranged to provide acceleration values for any drop height, Equation 6.

$$G = \frac{ae^{\frac{bsh}{t}}}{s} \qquad \text{Equation 6}$$

Because the stress energy method uses intrinsic properties, it provides cushion curves that are extremely flexible in their use and take less time to create than the original ASTM method. The curves can be manipulated by changing the thickness, drop height or static load or the cushion without having to perform another 10,000 drops.

Marcondes et al of Clemson University (2008) performed research focusing on applying the stress energy method to cushions of thicknesses ranging from one to three inches. The work provided valuable insight into the stress energy method and refined the testing procedures used. The work showed that cushion curves can be created by testing five cushion samples at three different energy levels. The three energy levels are chosen based on expected energy likely to be seen by the packaged product. These energy levels are generally between 10 and 50 in-lb/in^3, but may be varied depending on the specific environment faced by the packaged product. The third energy level should be approximately halfway between the high and low energy value (Marcondes et al 2008).

Marcondes' work showed that there was no statistically significant difference between linearized lines created with five energy levels and those created using three energy levels. This work was used to shorten the amount of time and samples needed to create cushioning curves. The statistical method used in this work compared the slope and intercept of the lines by using a standard t-test (Marcondes et al 2008).

Cushion Thickness:

Within the packaging industry, there is a need to use thinner foams for cushioning. This demand is fueled by the globalization of many industries. The industries involved take advantage of the lower costs of production from countries like China and India. Since manufacturing is shifting to these countries, measures are being taken to reduce the cost of shipping the final product from overseas to the United States. By using thinner foams, packaging engineers can design packages that are smaller, thus allowing more packages shipped per pallet, truck or sea container. Better container cube utilization reduces the overall cost of shipping by reducing the number of shipments used.

The desire for thinner foams opens up a question as to how the material behaves with cushioning of less than one inch in thickness. A study was conducted by Daum and Batt in 2007. Their research was conducted by creating cushion curves using the stress energy method with material greater than one inch in thickness and comparing it to curves created using material of less than one inch in thickness. Their work showed that there was a difference in curves created using material of less than one inch and curves created using material more than one inch. The material used during that research was expanded polystyrene with a density of 1.3 pcf (Daum and Batt 2009).

For this project, several materials and densities of materials were evaluated. These materials were chosen in order to expand upon the work done by Daum and Batt. The materials chosen are all commonly used materials so that the industry could benefit from the research. Cushion tests were conducted on closed cell foams with thicknesses both above and below one inch

` The first material was Arcel, a product manufactured by Nova Chemical. It is a 70/30 blend of Polystyrene and Polyethylene. Three commonly used densities were chosen for the research: 1.3, 1.5 and 1.9 lb/ft^3.

The next material chosen was expanded polyethylene with a density of 1.9 lb/ft^3 According to Lee (2006), "polyethylene foams are generally soft and resilient". This resilient nature makes them good for packaging applications where a product is expected to experience multiple drops.

The final material chosen for the research was expanded polypropylene with a density of 1.9 lb/ft^3. This material is gaining popularity in the markets due, in part, to its high recyclability. (Lee 2006).

CHAPTER THREE

MATERIALS & METHODS:

Test Equipment:

The test equipment used in this research was a Lansmont Cushion Tester model 23. The platen on the tester was fitted with a PCB piezoelectric accelerometer, model 353B15. All of the shock pulses were captured and analyzed with GHI WinCAT version 2.8.1 software. All equipment used was verified and compliant with ASTM D-1596. Figure 6 shows the equipment set up for testing

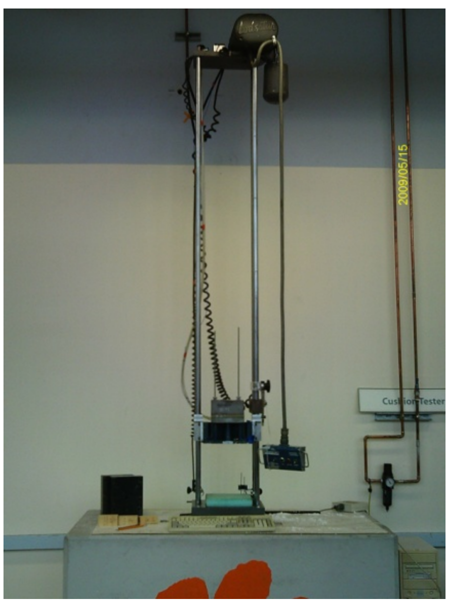


Figure 6: Lansmont Cushion Tester model 23

The equivalent free fall drop height was calculated using Lansmont Test Partner Velocity Sensor software version 2.0.1. The equivalent free fall drop height, h_{eq}, was calculated based on the impact velocity, V_i, measured just prior to impact with the cushion. This was done using the equation 7 where g is acceleration due to gravity.

$$h_{eq} = \frac{V_i^2}{2g} \qquad \text{Equation 7}$$

Equivalent free fall drop height was calculated because of friction in the testing equipment used. During testing, the platen was guided by rods during its free fall. These rods ensured that the platen landed flat every time. However, these rods impart friction into the system. Because of this friction, the actual measured drop height is typically greater than the equivalent free fall drop height.

During testing, the shock pulse was captured and analyzed. These pulses were filtered using an electronic filter to remove high frequency ‘noise’ that was captured during the drops. Figure 7 and Figure 8 show shock pulses before and after filtering. The equation 8 is used to determine the proper filtering frequency for the drops. The filter frequency, F_f, is a function of the duration of the shock pulse, τ_{10} such that the filter frequency is not 5 times the duration of the shock impulse.

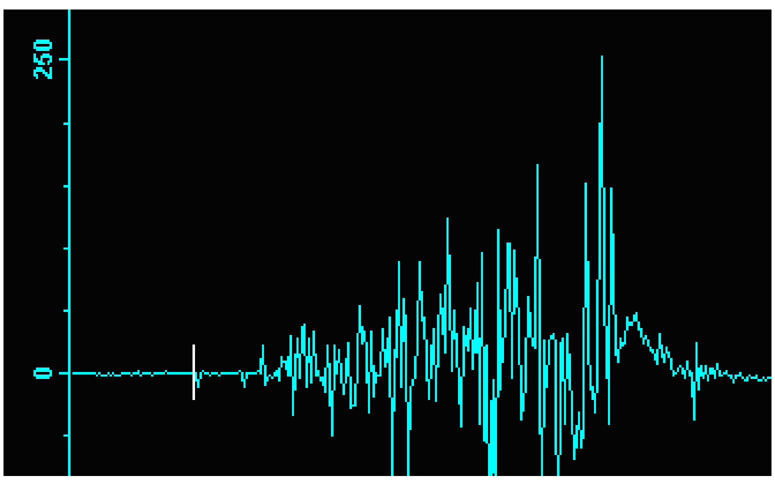


Figure 7: Example of Shock Pulse before filtering

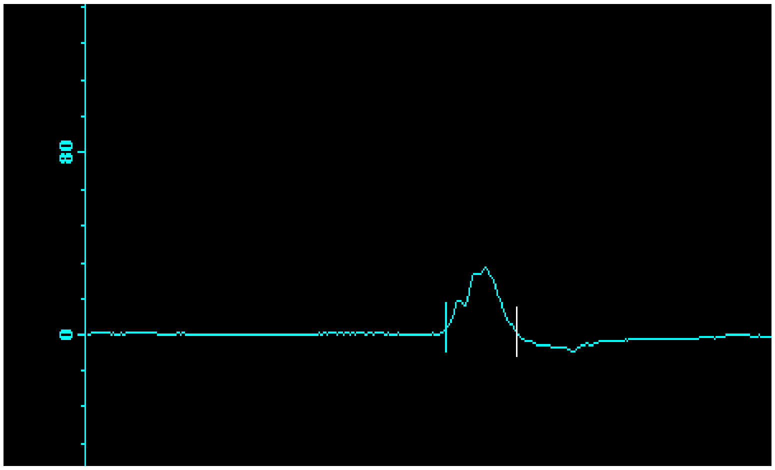


Figure 8: Example of Shock Pulse after filtering

$$F_f \geq 10\left(\frac{1}{2\tau_{10}}\right) \qquad \text{Equation 8}$$

Effective duration is determined by correctly picking points that are 10% of the peak pulse amplitude on the rise and decay of the shock pulse. This correction is needed because mechanically created shock pulses have a smooth rise and decay rather than the sharp boundaries of an idealized shock pulse as seen in Figure 9. (Department of Defense 2006).

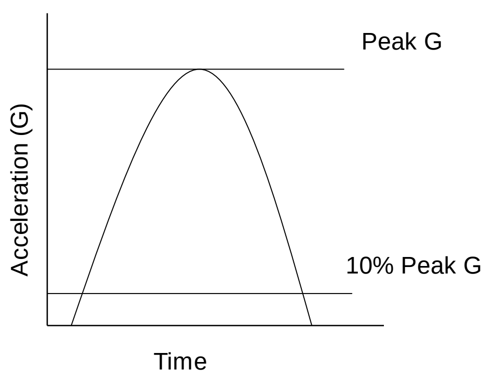


Figure 9: Idealized shock pulse

Materials:

The Arcel materials used in the study had three different densities: 1.3, 1.5 and 1.9 lb/ft³. Expanded polyethylene and expanded polypropylene were also studied. All of the samples were cut at Clemson University using a band saw. The material was stored in an environmental chamber set to 73°F and 50% relative humidity according to ASTM standards. Table 1 summarizes the materials used, the number of energy levels and the number of drops for the experiment. Table 2 provides the details for each drop, the expected energy level, bearing area, weight, static load, drop height and thickness of each sample for the testing. This test plan was used on each of five materials during testing.

Table 1: Summary of materials used during testing

Material Used	Energy Levels	Drops
Arcel 1.3 lb/ft³	3	150
Arcel 1.5 lb/ft³	3	150
Arcel 1.9 lb/ft³	3	150
EPE 1.9 lb/ft³	3	150
EPP 1.9 lb/ft³	3	150

Table 2: Testing specifications for each material

Sample	Expected Energy (in-lb/in³)	Area (in²)	Weight (lb)	Static Load (lb/in²)	Drop Height (in)	Thickness (in)
15A	15	12.8	12.8	1.0	15	1
15B	15	12.8	12.8	1.0	15	1
15C	15	12.8	12.8	1.0	30	2
15D	15	12.8	12.8	1.0	30	2
15E	15	12.8	25.6	2.0	22	3
25A	25	12.8	32.0	2.5	20	2
25B	25	12.8	32.0	2.5	20	2
25C	25	12.8	32.0	2.5	30	3
25D	25	12.8	32.0	2.5	30	3
25E	25	12.8	32.0	2.5	10	1
40A	40	19.2	64.0	3.3	36	3
40B	40	19.2	64.0	3.3	36	3
40C	40	19.2	64.0	3.3	12	1
40D	40	19.2	64.0	3.3	24	2
40E	40	19.2	64	3.3	24	2
Sample	**Expected Energy (in-lb/in³)**	**Area (in²)**	**Weight (lb)**	**Static Load (lb/in²)**	**Drop Height (in)**	**Thickness (in)**
15A	15	30.6	12.8	0.42	18	0.50
15B	15	30.6	12.8	0.42	18	0.50
15C	15	30.6	12.8	0.42	27	0.75
15D	15	30.6	12.8	0.42	27	0.75
15E	15	30.6	12.8	0.42	18	0.50
25A	25	30.6	32.0	1.05	18	0.75
25B	25	30.6	32.0	1.05	18	0.75
25C	25	30.6	32.0	1.05	18	0.75
25D	25	30.6	32.0	1.05	12	0.50
25E	25	30.6	32.0	1.05	12	0.50
40A	40	12.8	19.2	1.50	20	0.75
40B	40	12.8	19.2	1.50	13	0.50
40C	40	12.8	19.2	1.50	20	0.75
40D	40	12.8	19.2	1.50	20	0.75
40E	40	12.8	19.2	1.50	13	0.50

The testing was conducted in accordance with ASTM D-1596, except for the number of impacts. The curves were created using the stress energy method, which allows for greater usability of the data and less samples required. Each shock pulse was filtered and analyzed. The peak acceleration was recorded. The material was allowed to rest for at least one full minute before the next impact occurred. In order to plot Dynamic Stress, the peak acceleration, G, was multiplied by the static load, s, used in testing. Dynamic Energy was determined by multiplying static load, s, by equivalent free fall drop height, h, and dividing by thickness, t, of the cushioning material.

Data Treatment:

The data from each material were used to test if cushion curves created from material with thicknesses greater than one inch were different than cushion curves created from material with thicknesses less than one inch. The data was compared in three ways.

Method I. The first method of comparison was transforming the cushion curves into linearized curves and performing regression analysis on the linearized data. The regression analysis tested for differences between the slopes and the intercepts of the lines created with data from cushions greater than one inch and with data from cushions less than one inch.

Regression analysis was used to determine if a difference in the curves existed. The statistical method selected was based on a second-order model where the second-order term accounts for interaction between the two variables, less than one inch and greater than one inch (Mendenhall, 1996). The general form of this model is

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \qquad \text{Equation 9}$$

In this model β_0 represents the intercept of the line greater than one inch. β_1 represents the slope of the line greater than one inch. β_2 represents the difference in slopes between the lines for greater than one inch and less than one inch. β_3 represents the interaction between slopes for greater than one inch and less than one inch.

If the lines are different, then the third term, β_2 , will be statistically significant, having a p-value of less than 0.05. This means that there is in fact some sort of interaction between the lines created with data from material less than one inch and from lines created with data from material greater than one inch.

This method was done for comparison of the curves created from material greater than one inch in thickness and for the curves created from material less than one inch in thickness.

Regression analysis was also performed in order to compare the curves created from material less than one inch in thickness to curves created from the combined (pooled) data. This pooled data included data from material greater than one inch in thickness and from the material less than one inch in thickness. This pooling of data was used because if there is no statistical difference, then accurate cushion curves could be created with minimum additional lab testing. The testing required would be on cushions less than one inch in thickness at three energy levels. This data could be added, or pooled, with the existing data for materials greater than one inch. This would result in substantially less time and materials required to create accurate cushion curves for materials less than one inch in thickness.

A Stress energy curve was created by combining the data points from both sets of data. The new stress energy curve was statistically compared with the stress energy curve created from data less than one inch in thickness.

Method II. The second method of comparison involved looking at the predicted acceleration values, G's, from the curve created with data from cushions greater than one inch and from data with cushions less than one inch. The acceleration values were compared using the difference between the two values and the percent relative difference between the two values, Equation 10

$$\frac{X_1 - X_2}{(\frac{X_1 + X_2}{2})} * 100\% \qquad \text{Equation 10}$$

Method III. The raw data collected from the testing performed with cushioning less than one inch in thickness was compared to the predicted acceleration values from the curves created with the data from cushioning greater than one inch. The acceleration values were compared using the difference, Equation 11 and the percent difference, Equation 10 between the two acceleration values.

$$X_1 - X_2 \qquad \text{Equation 11}$$

CHAPTER FOUR

RESULTS & DISCUSSIONS:

Initial investigation of the scatter plots of different materials showed that the stress-energy relationship could be described as increasing at an increasing rate. This relationship is best described as exponential. This relationship has been seen in other studies of polymeric material, such as those performed by Marcondes et al (2008), Daum and Batt (2009) and Burgess (1990). It can also be seen that as the energy density increases, the variability among the data increases as well. Figure 10 shows an example of the stress energy curves for the materials tested. Appendix A contains the Stress-Energy curves for all of the materials tested. The values on the y axes have been removed because of their proprietary nature. An exponential curve was fit to the data. The curve fit had a coefficient of correlation (R-square) value of 0.99 for the majority of the data sets. None of the data sets had an R-square value of less than 0.87. Table 3 gives a summary of average for drops 1-5 R-square values associated with each curve.

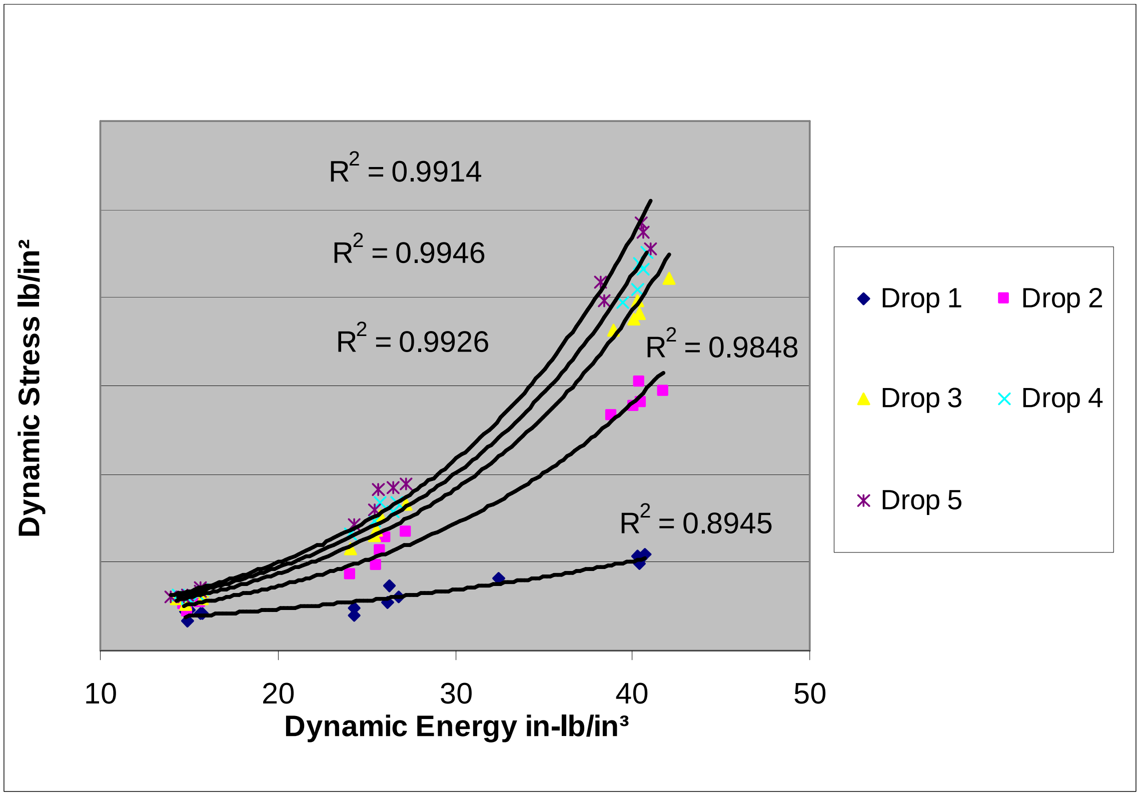


Figure 10: Example of Stress-Energy Curve for Arcel 1.9 pcf >1 inch

Table 3: Summary of R-square values for Stress-Energy Curve

Material	Thickness (in)	R-square (average drop 1-5)
Arcel 1.3 lb/ft³	>1 inch	0.98
Arcel 1.3 lb/ft³	<1 inch	0.99
Arcel 1.5 lb/ft³	>1 inch	0.98
Arcel 1.5 lb/ft³	<1 inch	0.99
Arcel 1.9 lb/ft³	>1 inch	0.97
Arcel 1.9 lb/ft³	<1 inch	0.97
EPP 1.9 lb/ft³	>1 inch	0.91
EPP 1.9 lb/ft³	<1 inch	0.98
EPE 1.9 lb/ft³	>1 inch	0.96
EPE 1.9 lb/ft³	<1 inch	0.99

Method I. After the initial data were collected from the stress-energy curves, the data points were linearized for easier statistical comparison. The dynamic stress was transformed by taking the natural logarithm of the Dynamic Stress. This transformation linearized the data. The data was again plotted and visually inspected. Figure 11 is an example of the linearized Stress-Energy curve for Arcel 1.9 pcf material. Appendix B contains the linearized curves for all five drops for all five materials. The values on the y-axis were withheld due to their proprietary nature.

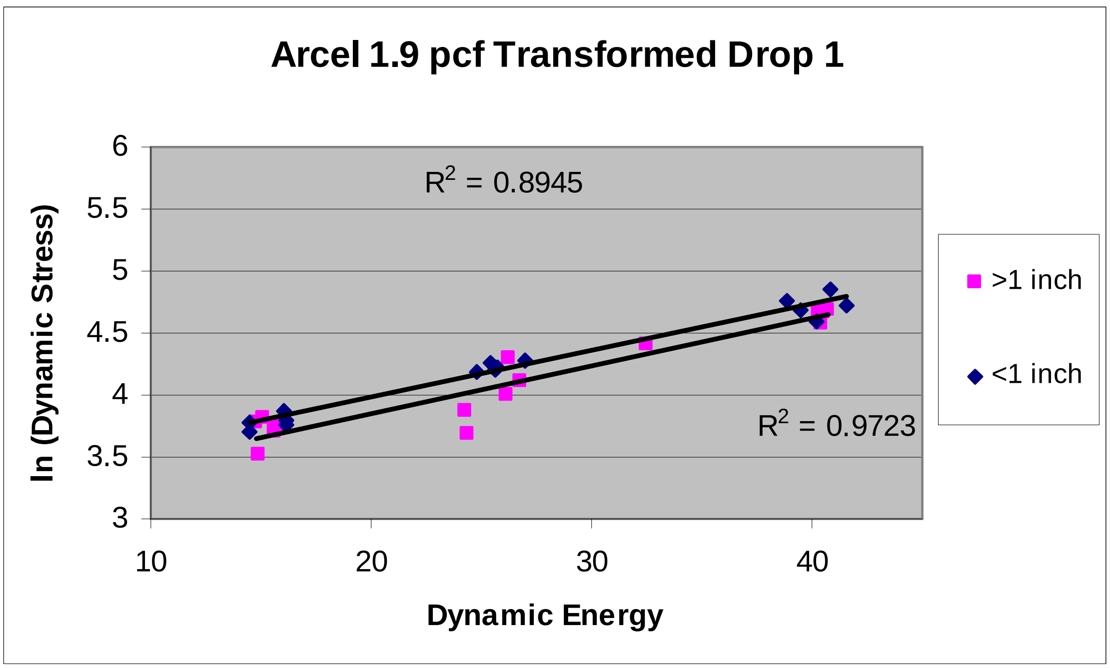


Figure 11: Example of linearized Stress-Energy curve

As can be seen from the Figure 11, the relationship is very linear. The R-square values are all above 0.89 with the majority of them closer to 0.99. These high R-square values mean that the linearized model relationship is a very good fit for the data. The lines were then compared to each other to see if a statistical difference existed. Linear regression (Equation 8) was used to determine if a statistical difference existed between the line created with data from greater than one inch and those created with data from less than one inch. Figure 12 is an example of the linear regression equation from Arcel 1.9 lb/ft³. SAS was used to determine that the lines from greater than one inch and less than one inch were not statistically different. Table 4 shows the results of the statistical analysis.

$$Y = 2.793 - 0.261X_1 + 0.056X_2 + 0.009X_3$$

Figure 12: Linear regression equation for Arcel 1.9 lb/ft³

Table 4: Statistical comparison of transformed data

Material	Results of Statistical Comparison with α=0.05				
	1st Impact	2nd Impact	3rd Impact	4th Impact	5th Impact
Arcel 1.3 lb/ft³	Stat Dif	Stat Dif	Stat Dif	Stat Dif	Stat Dif
Arcel 1.5 lb/ft³	Not Stat Dif	Stat Dif	Stat Dif	Stat Dif	Stat Dif
Arcel 1.9 lb/ft³	Not Stat Dif	Not Stat Dif	Not Stat Dif	Not Stat Dif	Not Stat Dif
EPE 1.9 lb/ft³	Stat Dif	Stat Dif	Stat Dif	Stat Dif	Stat Dif
EPP 1.9 lb/ft³	Not Stat Dif	Not Stat Dif	Stat Dif	Stat Dif	Stat Dif

These differences are similar to the ones discovered by Daum and Batt (2007) in their earlier work, showing a statistical difference between the cushion curves created by data collected with material greater than one inch and material less than one inch in thickness. Arcel 1.9 lb/ft³ shows no statistical differences in any of the five drops. This may be because the material did not bottom out at the highest energy level of 40 for the material less than one inch in thickness. Bottoming was observed on the other four materials. This could result in higher predicted acceleration values for cushion curves created from materials that have bottomed out.

If the material bottoms out, the resulting acceleration value would be high. This high acceleration value could cause the stress energy curve to be influenced to predict higher acceleration values. Three points were utilized to make this stress energy curve. If one of the end points were moved, the entire curve could be influenced by that move. Thus, the bottoming out could have influenced the entire stress energy curve for materials less than one inch. This influence may be responsible for the statistical differences in the two curves (greater than one inch and less than one inch.) Since the Arcel 1.9 lb/ft^3 did not bottom out during testing, it makes sense that the there would be no statistical differences between both sets of curves.

The results for the comparison of the curves created from pooled data to the curves created from data from materials less than one inch in thickness showed no statistical differences for any of the five materials on any of the five drops. This lack of statistical difference suggests that the curves created from both sets of data would accurately predict the acceleration values for materials ranging from 0.5 inches to 3 inches in thickness. This would reduce the amount of time and material required to create cushion curves for thinner materials

The evidence of the statistical differences led to an investigation of whether there was a practical difference in the data. Although some of the curves might be statistically different, it does not necessarily mean that the difference will be of significant size to be a problem for a packaging scientist when designing a package system for distribution. In order to compare the values for a practical difference, two different methods of comparisons where used.

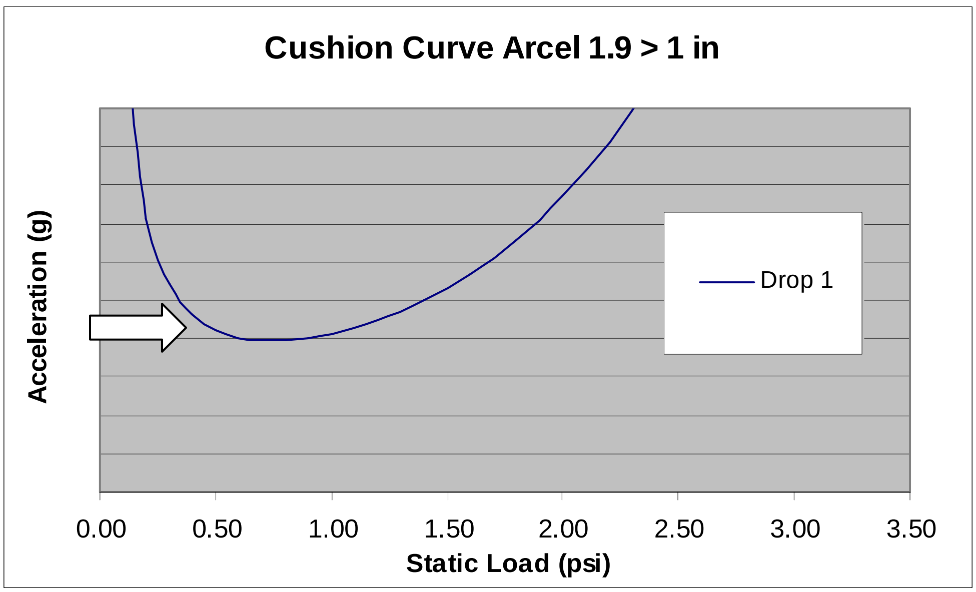
Method II This method was a comparison based on in-lab variation allowed by ASTM while creating cushion curves. ASTM allows a 1-4 G, or 5% of the peak acceleration value difference between curves created in the same lab. Equation 10 shows how percent difference was calculated. This method compared the predicted acceleration values between curves created with data greater than one inch and from data less than one inch. The data were compared over a range of common static loads, drop heights and cushion thicknesses. Table 3 summarizes the percent differences between the two curves. The comparison shows that there are significant practical differences larger than the ASTM allowance between the two curves.

Table 5: Comparison of common drop heights and static loads for curves produced with less than 1 inch and greater than 1 inch data

Material	18 in	24 in	36 in
	Mean percent difference in acceleration (%G)	Mean percent difference in acceleration (%G)	Mean percent difference in acceleration (%G)
Arcel 1.3 lb/ft³	9.22	14.18	20.86
Arcel 1.5 lb/ft³	10.37	11.93	13.46
Arcel 1.9 lb/ft³	12.05	11.22	10.39
EPE 1.9 lb/ft³	6.98	10.86	16.06
EPP 1.9 lb/ft³	11.79	18.24	20.87

The differences between the two cushion curves showed a trend that at lower drop heights the percent difference between the cushion curves were smaller and as the drop height increased, the percent difference between the cushion curves increased. All of the differences were greater than 5% which is more than the ASTM allowance for in-lab cushion curves.

Method III. Another method used to compare the practical difference was a comparison of actual data from drops less than one inch in thickness to the predicted values from curves created with data from greater than one inch. Figure 13 shows how the comparisons were made. The arrow on the cushion curve indicates the acceleration value read from the curve at the static load of 0.42 lb/in². The comparison showed that there were significant differences between the predicted and actual acceleration values. Table 6 contains the material, energy level, and difference range for the data. This table is a summary for data shown in Appendix C. For all of the materials tested, the differences were dependent upon the energy levels. The lowest energy level of 15 in-lb/in³ had less severe differences than the largest energy level of 40 in-lb/in³.



Static Load (lb/in²)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference
0.42	25.92	0.75	104.33	92.72	11.60147

Figure 13: Example of comparisons for Arcel 1.9 lb/ft³

Table 6: Comparison of predicted acceleration values from curves created with >1inch data to actual acceleration for material less than one inch in thickness

Material	15 in-lb/in³	25 in-lb/in³	40 in-lb/in³
	Difference Range (G)	Difference Range (G)	Difference Range (G)
Arcel 1.3 lb/ft³	2.34-18.25	0.81-26.06	2.17-130.85
Arcel 1.5 lb/ft³	0.22-15.97	10.76-54.79	1.71-69.76
Arcel 1.9 lb/ft³	2.30-13.17	1.13-13.68	10.10-72.12
EPE 1.9 lb/ft³	8.94-40.52	0.88-20.17	5.56-42.24
EPP 1.9 lb/ft³	0.27-12.92	0.53-4.8	5.06-43.18

CHAPTER FIVE

CONCLUSIONS:

A significant statistical difference exists between curves created with data from less than one inch in thickness and curves created with data from greater than one inch in thickness. Because of this statistical difference, the practical differences between the two curves were evaluated. The range in differences between predicted and actual acceleration values is large enough that a practical and significant difference is present. These results support the previous work performed by Daum and Batt (2009). Because of this significant difference, it can be concluded that data from existing stress-energy curves cannot be used to predict the acceleration of drops on cushions less than one inch in thickness.

The R-square values from all of the curves, both less than and greater than one inch, created were above 0.87, with the majority of the curves having R-square values higher than 0.95. These high R-square values mean that the stress energy model is a good model for predicting acceleration values of the closed cell cushioning material. If package designers wish to use materials less than one inch in thickness, they will have to develop new cushion curves from data collected with materials less than one inch.

A statistical comparison using regression analysis showed that the stress-energy curves for materials greater than one inch and less than one inch showed that statistical differences do exist for four of the five materials tested. These results were similar to the ones discovered by Daum and Batt (2009).

Comparison of predicted acceleration values from cushion curves created from materials greater than one inch and less than one inch showed differences larger than the ASTM allowance of 5%. Since the differences were greater than 5%, the cushion curves created were deemed different. The difference between curves increased as the drop height for the cushion curves increased.

Comparison of predicted acceleration values from cushion curves created with materials greater than one inch and actual acceleration values from impacts on cushions of less than one inch showed significant differences. The trends seen were smaller differences at low energy levels and larger differences at higher energy levels.

CHAPTER SIX

RECOMMENDATIONS:

Further work should be done to determine what is happening with these thin foams. One idea is that the material is bottoming out under these higher energies. This bottoming out may be causing higher acceleration values and as such, causing the prediction values from the greater than one inch data to be wrong. This bottoming out may explain why the two curves have higher differences at higher energy levels. Stress-strain testing may be used to determine how the material behaves at different thicknesses.

Another point to consider is to see if there are statistical differences with curves created with cushions of just one inch compared to curves created with cushions of just three inches. These differences may help to further explain how much of the shock absorption is because of the mechanical properties of the material, and how much is due to the air trapped in the closed cells.

A further point of recommendation is to look into the pooled data to determine how accurately the cushion curves created from the pooled data predicts acceleration values. The acceleration values from the cushion curves could be compared as in Method III in this study. This further work would determine if less time could be used to create cushion curves. If it is possible to pool data above and below one inch in thickness and accurately predict cushioning properties for both, it would benefit the industry by reducing the amount of time and material required for creating cushion curves.

APPENDIX A:

Scatter plots of all data collected. The values on the Y-axis have been withheld due to their proprietary nature.

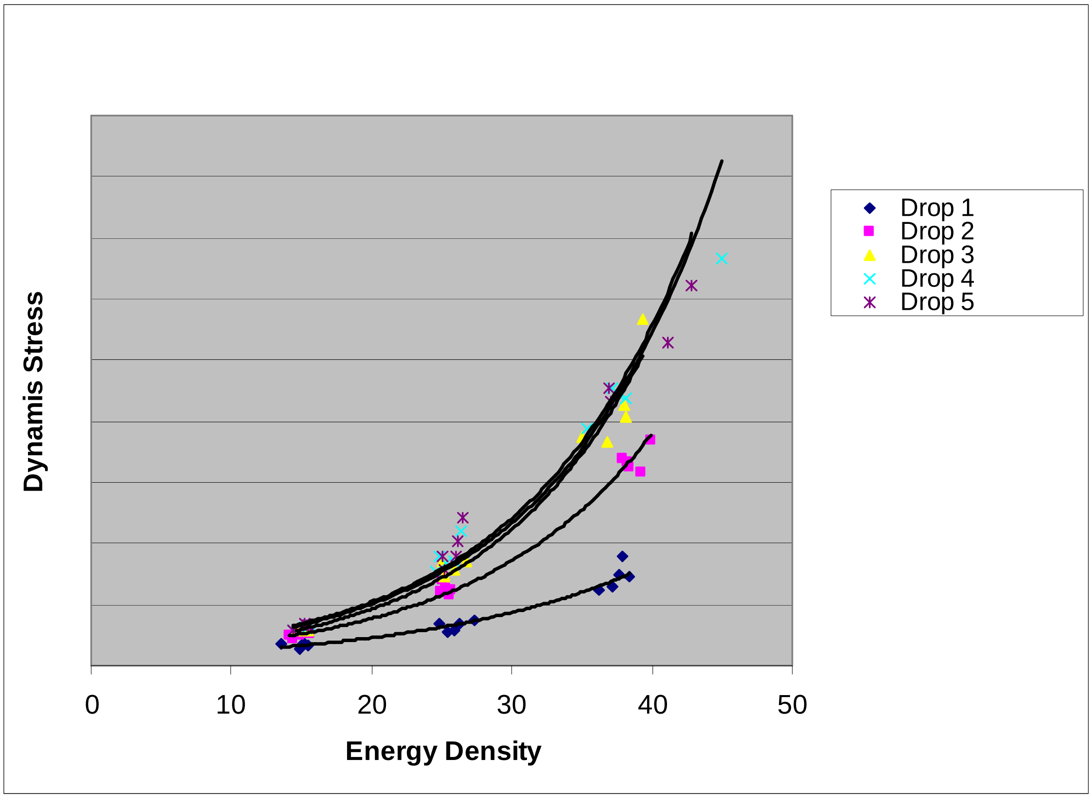


Figure 1: Scatter plot of data for Arcel 1.3 lb/in³ greater than 1 inch thickness

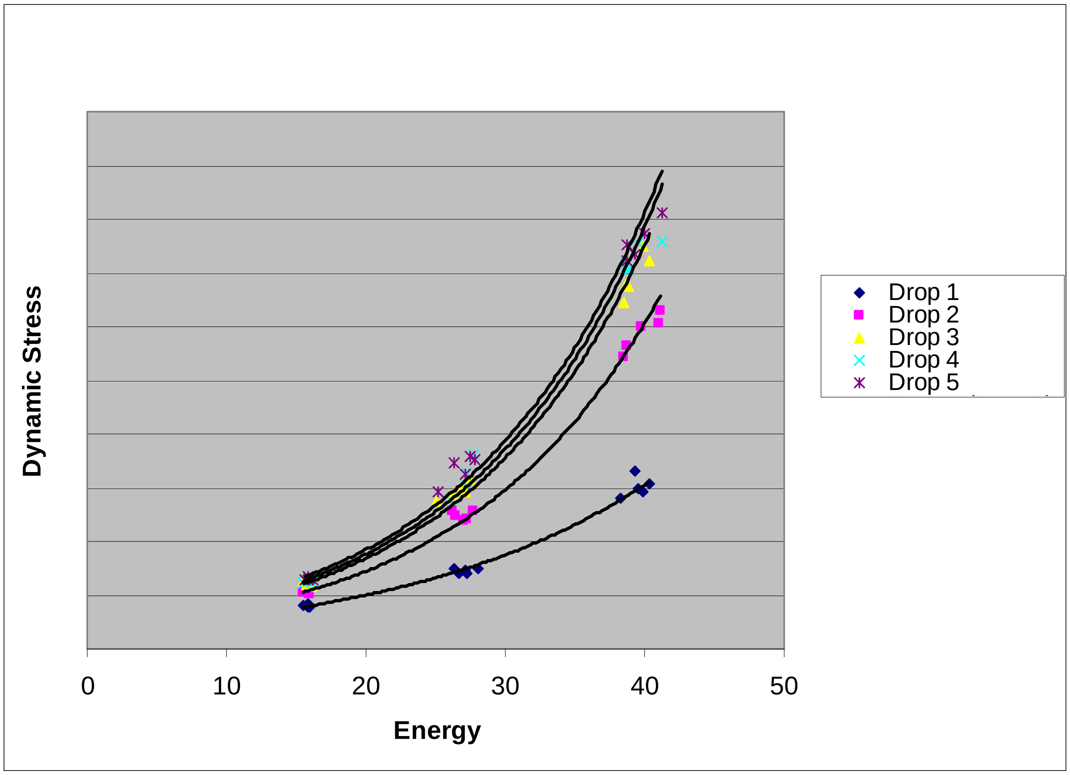


Figure 2: Scatter plot of data for Arcel 1.3 lb/in³ less than 1 inch thickness

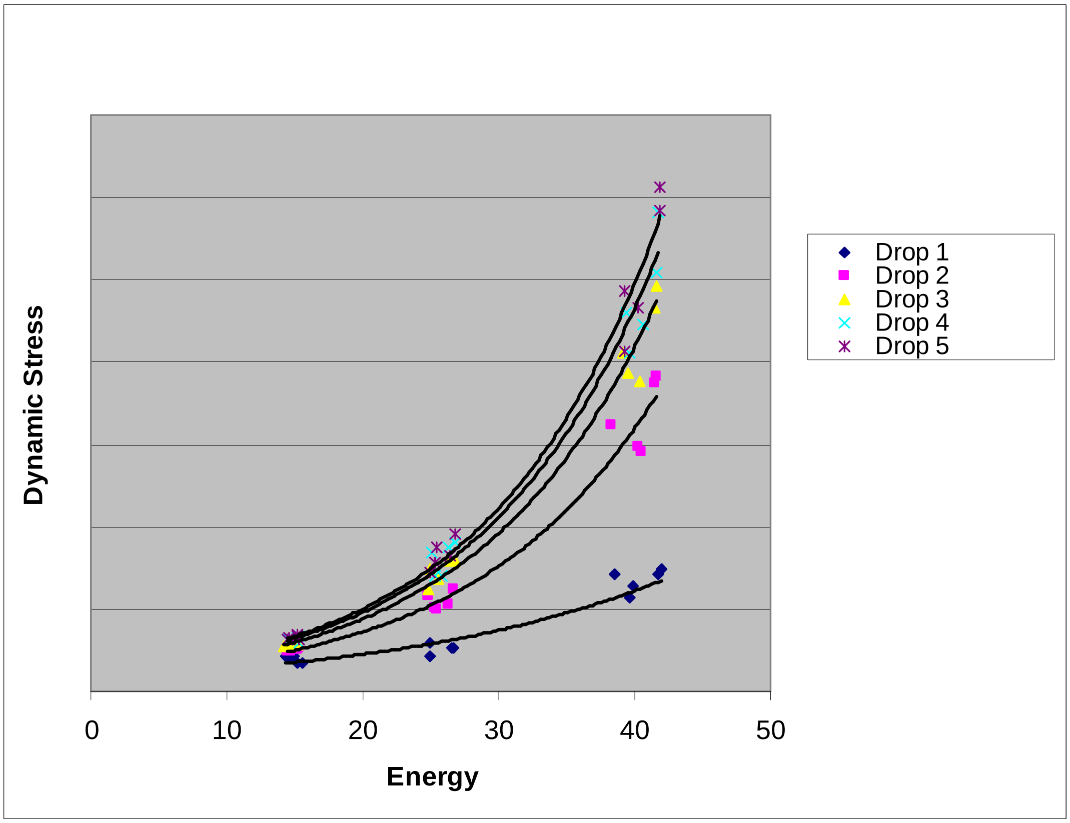


Figure 3: Scatter plot of data for Arcel 1.5 lb/in³ greater than 1 inch thickness

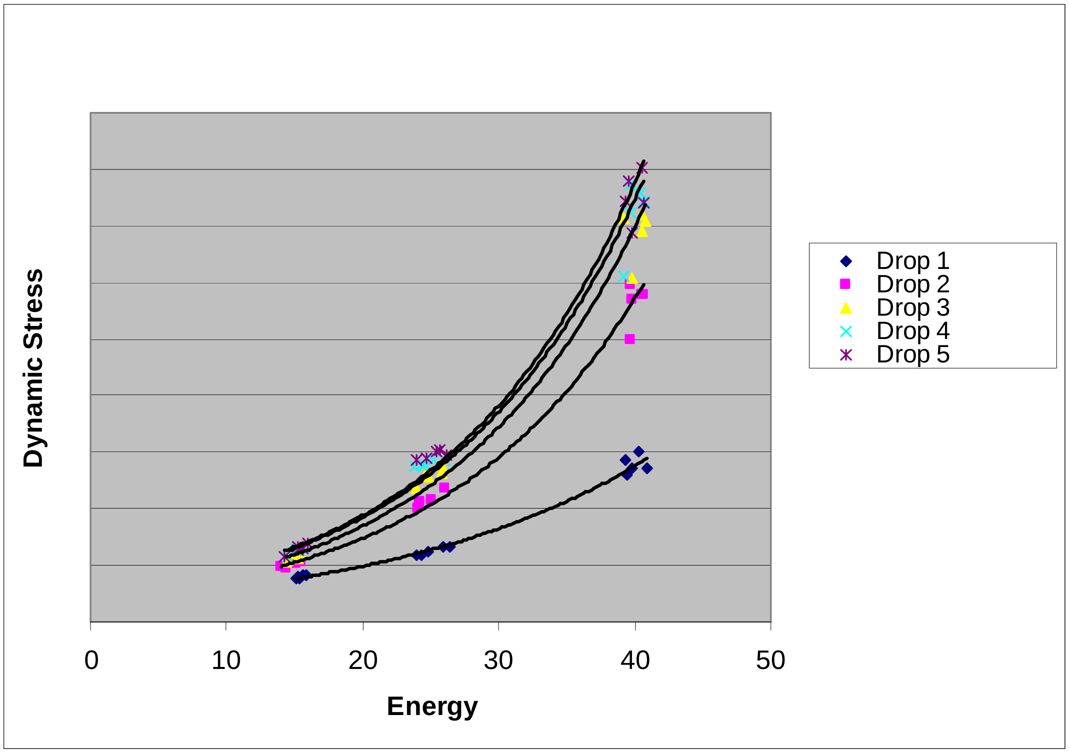


Figure 4: Scatter plot of data for Arcel 1.5 lb/in³ less than 1 inch thickness

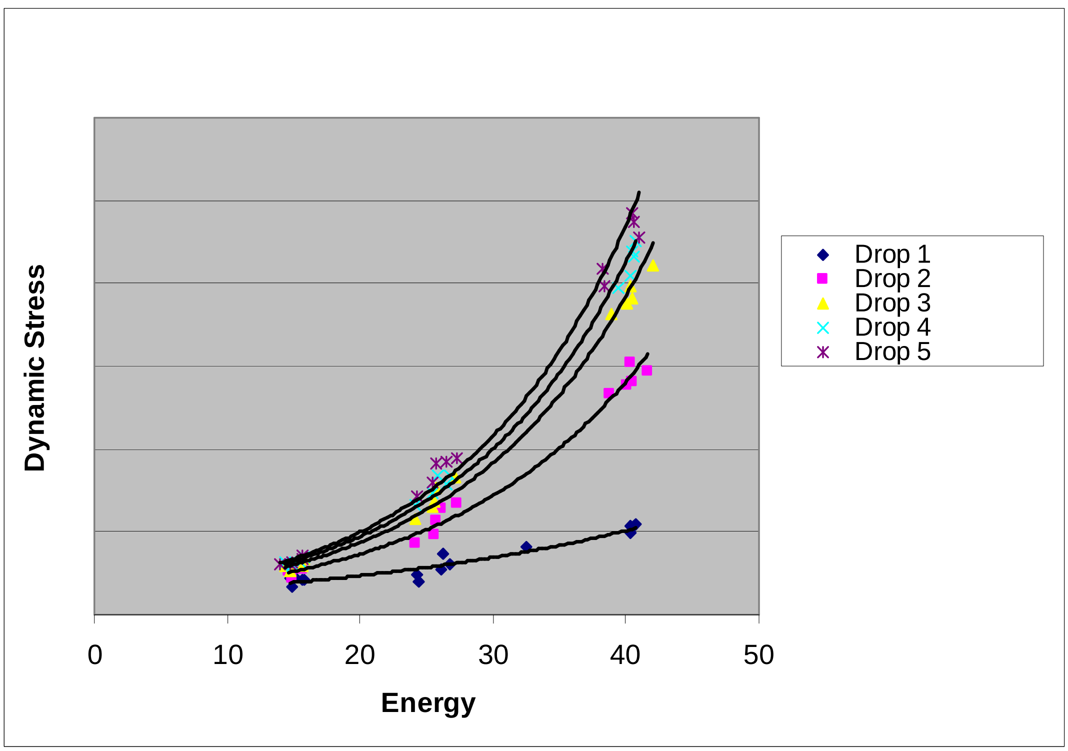


Figure 5: Scatter plot of data for Arcel 1.9 lb/in³ greater than 1 inch thickness

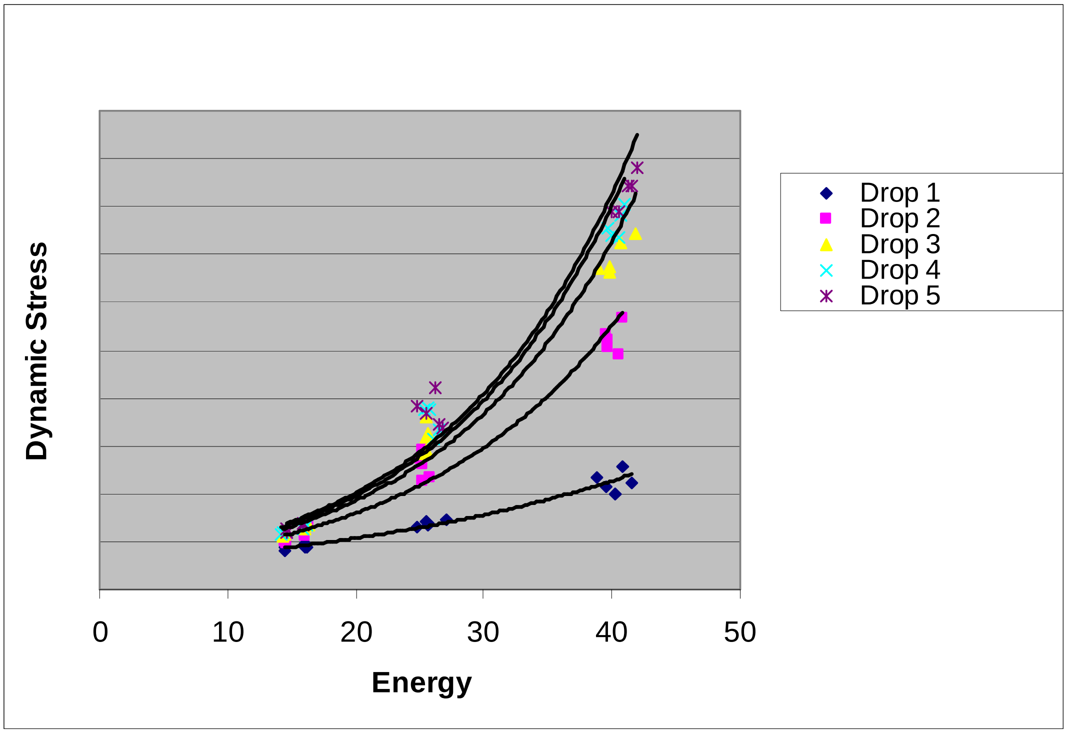


Figure 6: Scatter plot of data for Arcel 1.9 lb/in³ less than 1 inch thickness

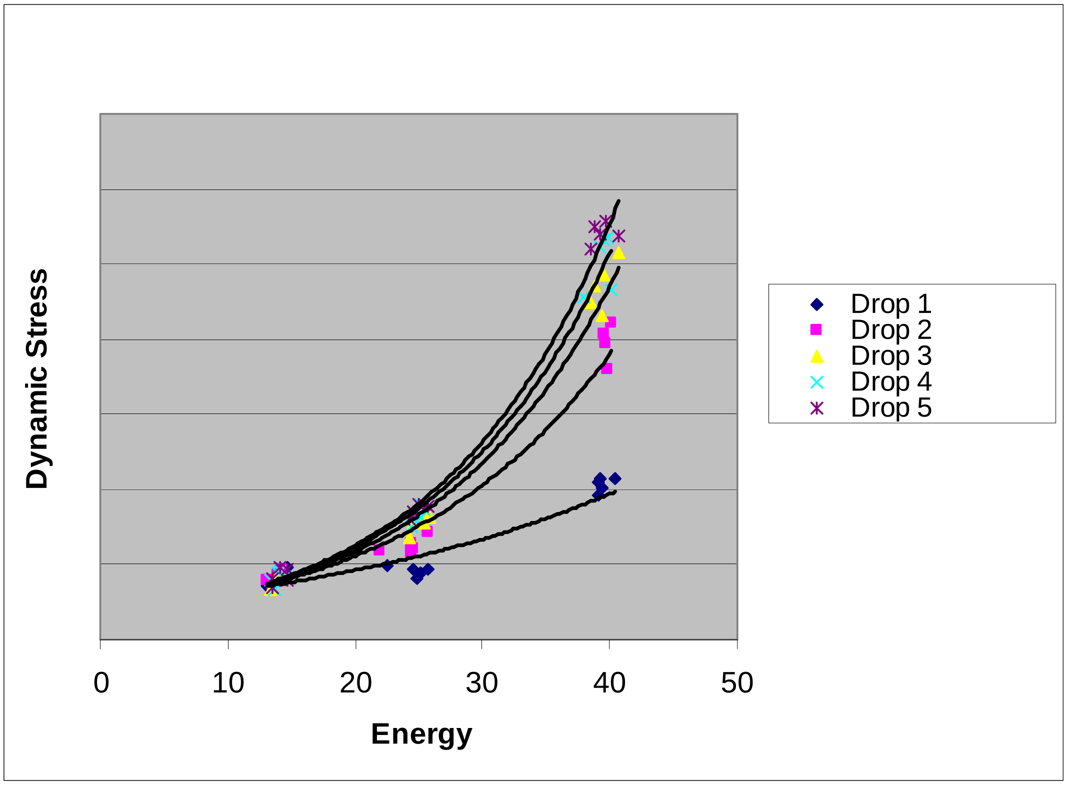


Figure 7: Scatter plot of data for expanded polypropylene 1.9 lb/in³ greater than 1 inch thickness

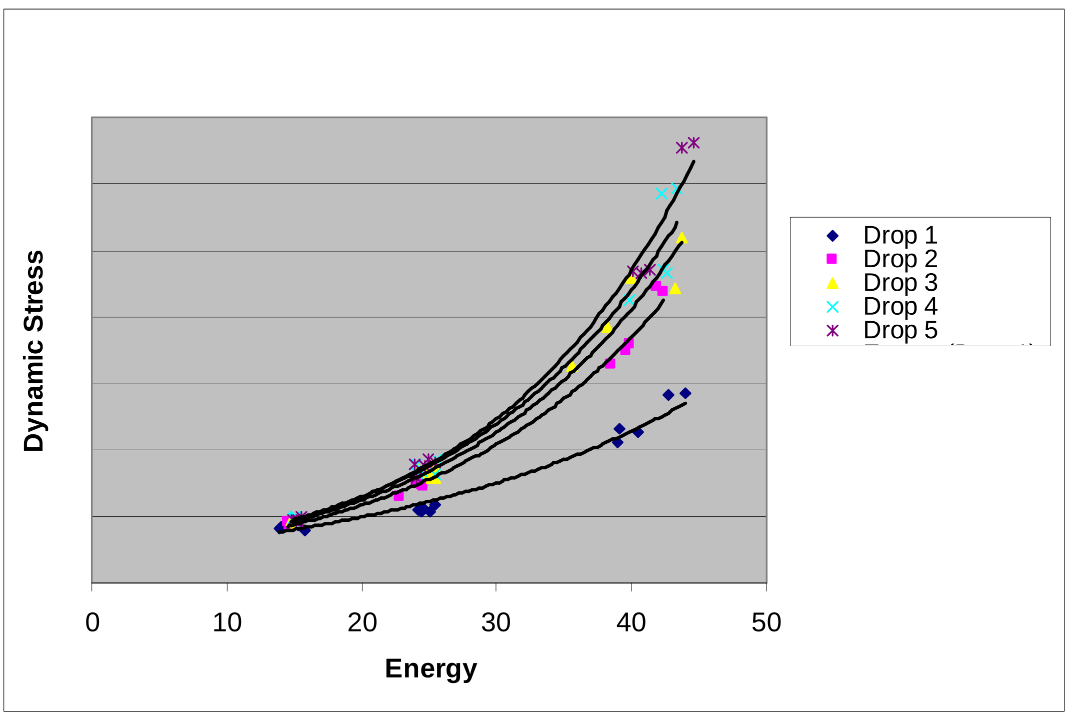


Figure 8: Scatter plot of data for expanded polypropylene 1.9 lb/in³ less than 1 inch thickness

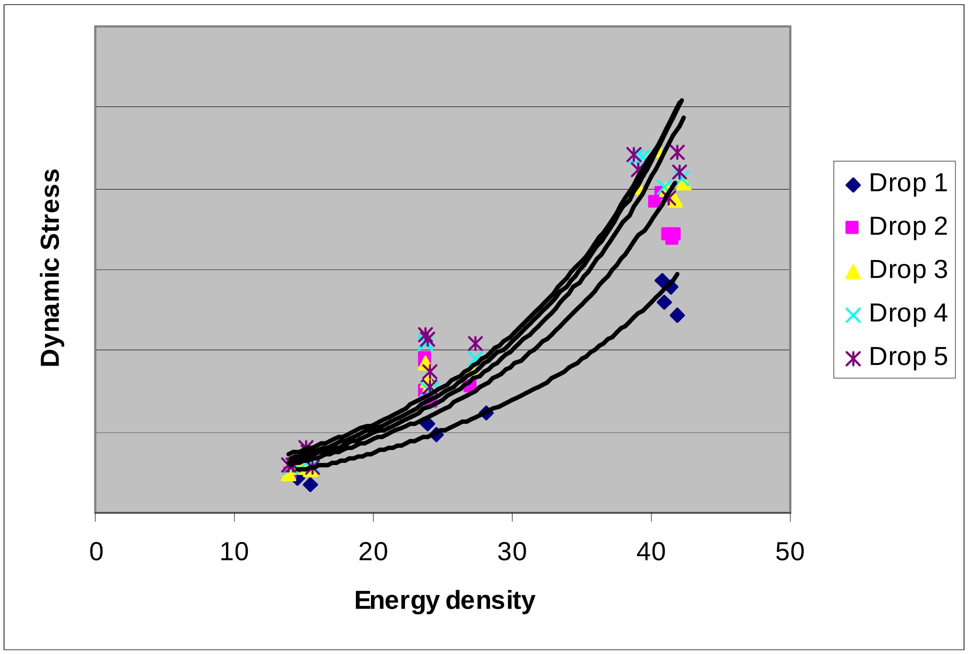


Figure 9: Scatter plot of data for expanded polyethylene lb/in³greater than 1 inch thickness

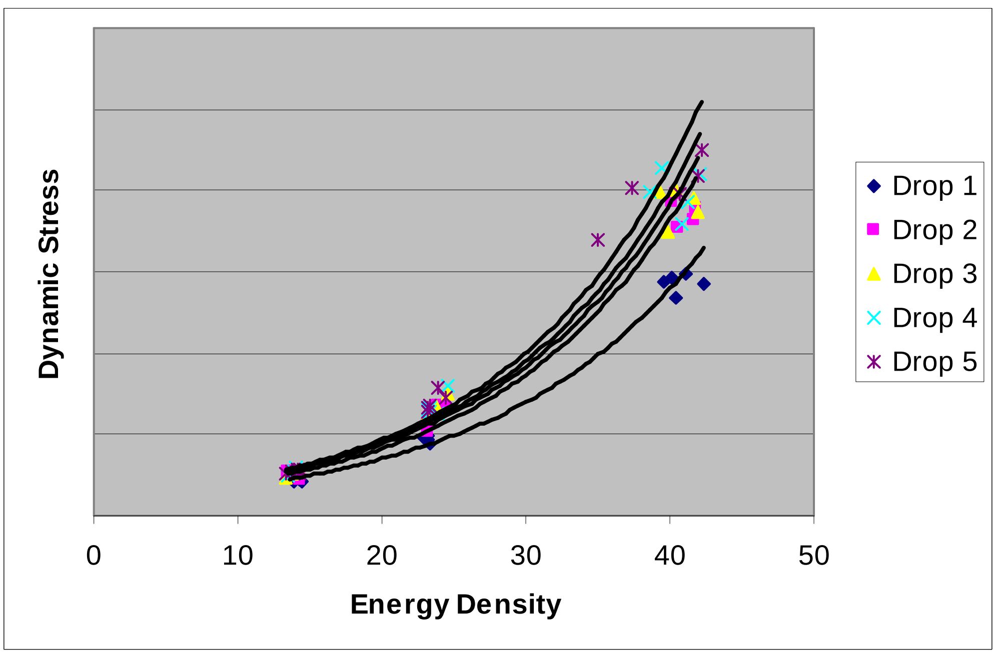


Figure 10: Scatter plot of data for expanded polyethylene lb/in³ less than 1 inch thickness

APPENDIX B:

Transformed stress energy curves for all materials tested. The values on the Y-axis have been withheld due to their proprietary nature.

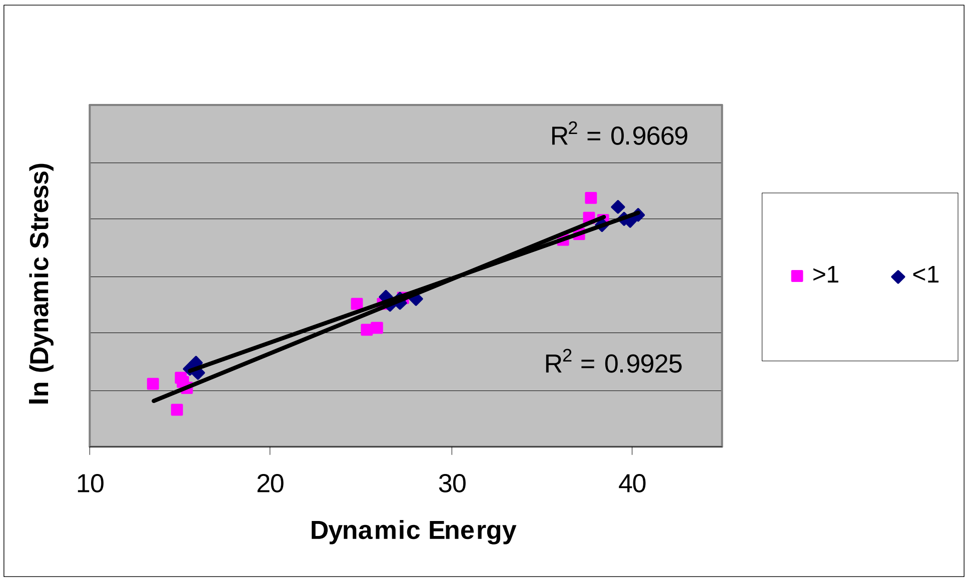


Figure 1: Linearized data for Arcel 1.3 pcf Drop 1 for less than and greater than 1 inch

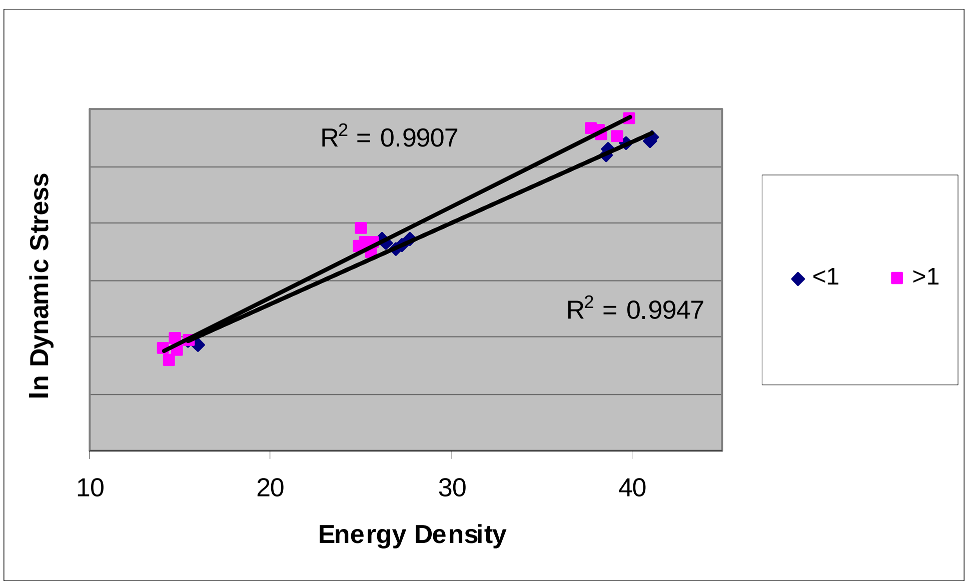


Figure 2: Linearized data for Arcel 1.3 pcf Drop 2 for less than and greater than 1 inch

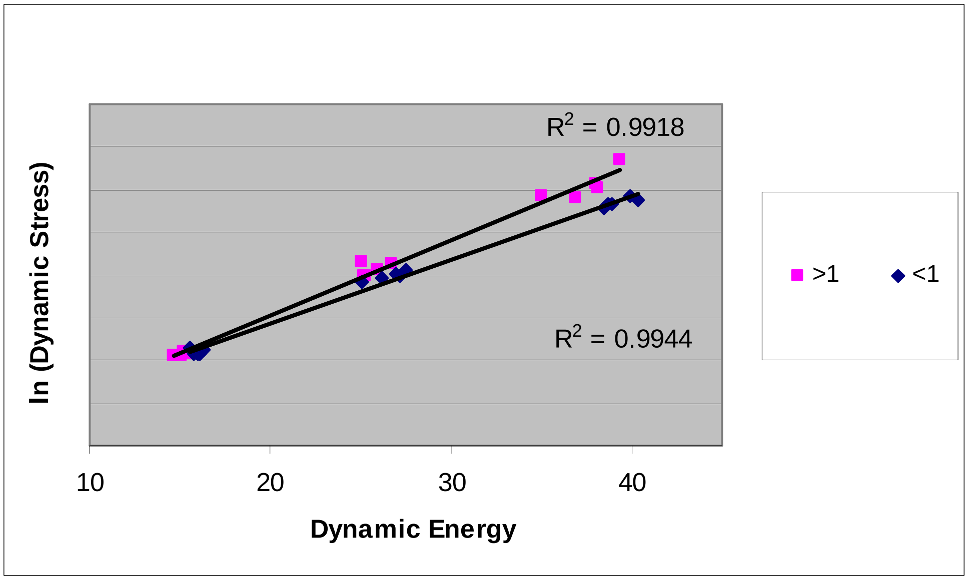


Figure 3: Linearized data for Arcel 1.3 pcf Drop 3 for less than and greater than 1 inch

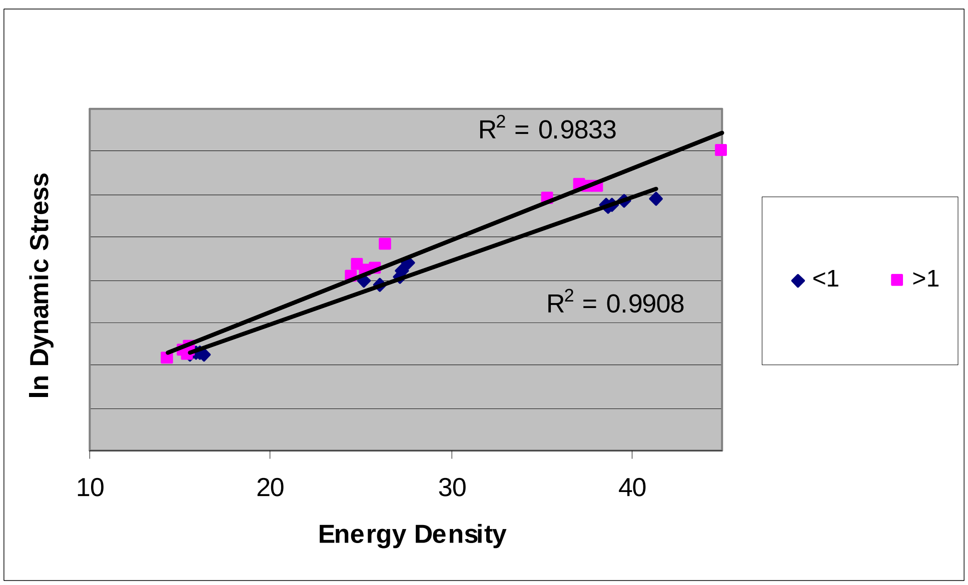


Figure 4: Linearized data for Arcel 1.3 pcf Drop 4 for less than and greater than 1 inch

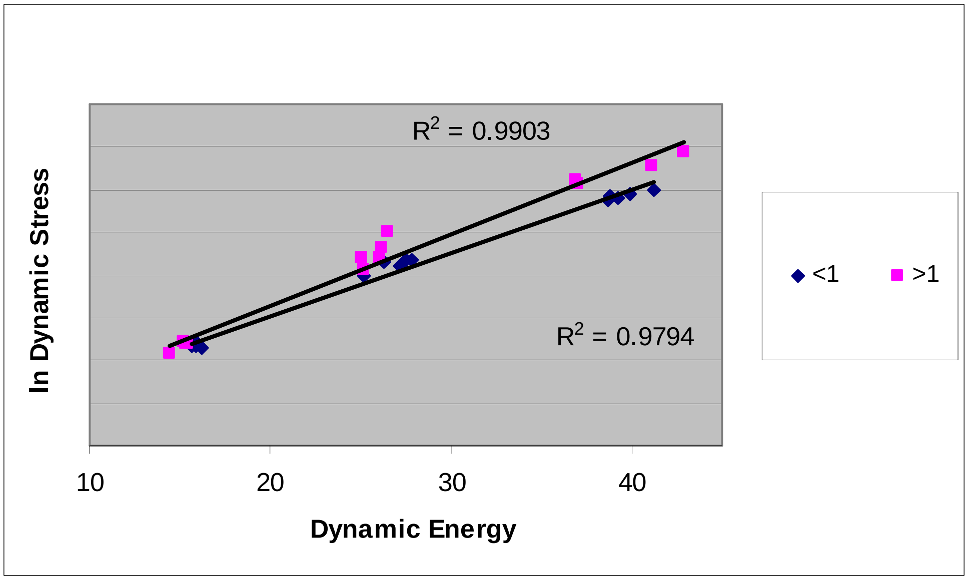


Figure 5: Linearized data for Arcel 1.3 pcf Drop 5 for less than and greater than 1 inch

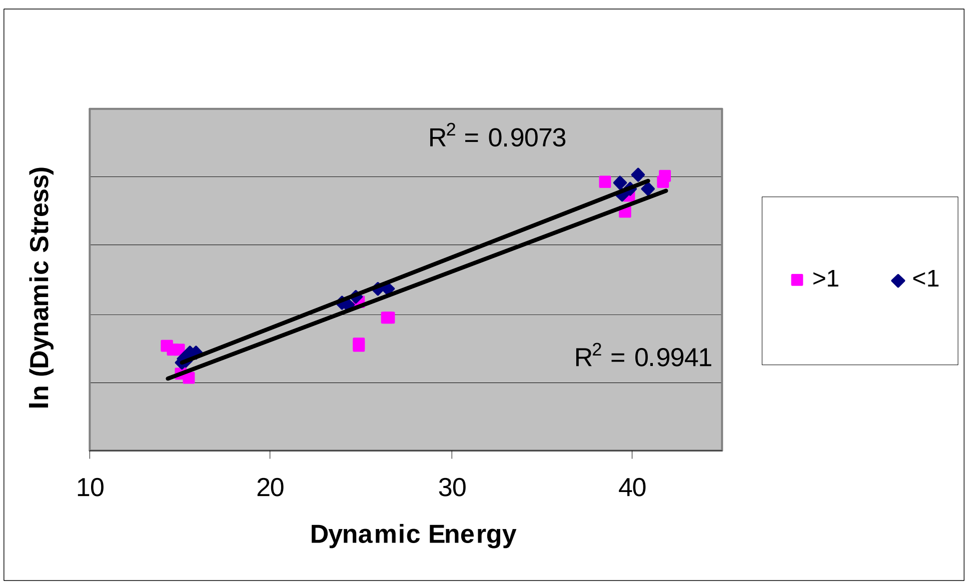


Figure 6: Linearized data for Arcel 1.5 pcf Drop 1 for less than and greater than 1 inch

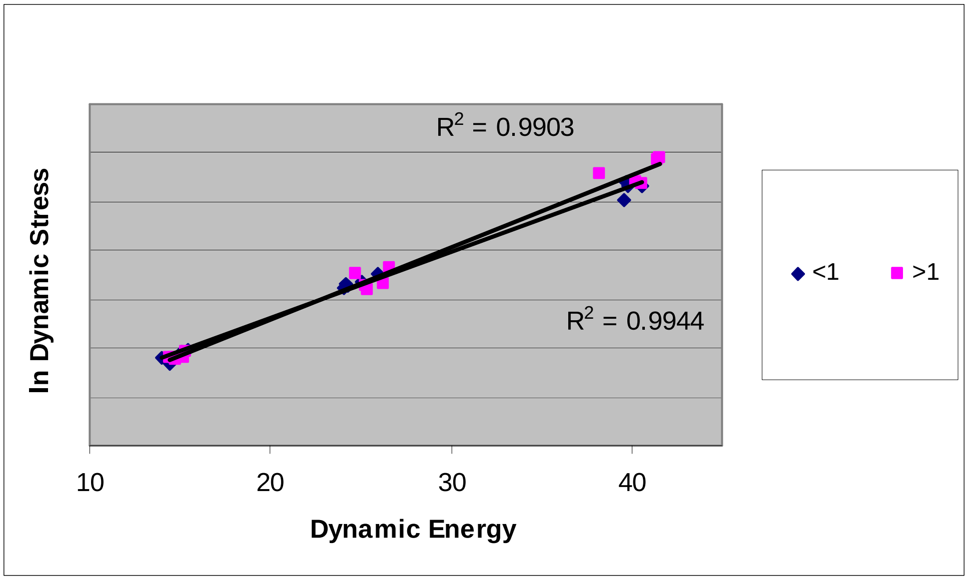


Figure 7: Linearized data for Arcel 1.5 pcf Drop 2 for less than and greater than 1 inch

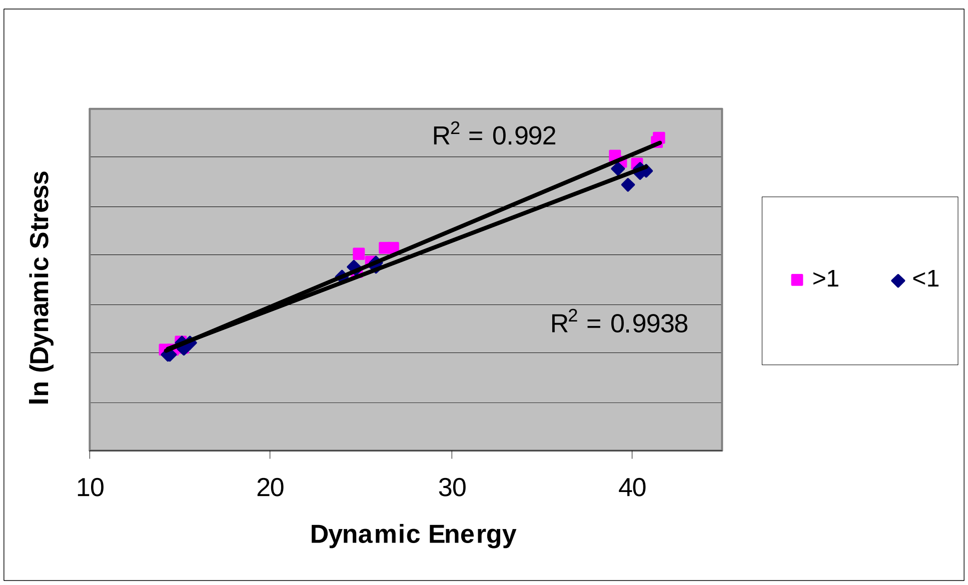


Figure 8: Linearized data for Arcel 1.5 pcf Drop 3 for less than and greater than 1 inch

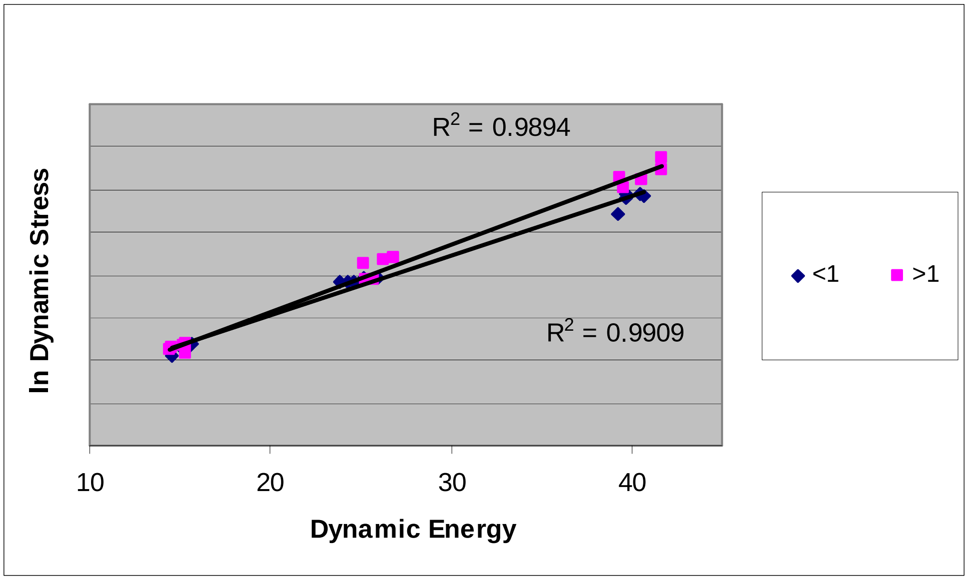


Figure 9: Linearized data for Arcel 1.5 pcf Drop 4 for less than and greater than 1 inch

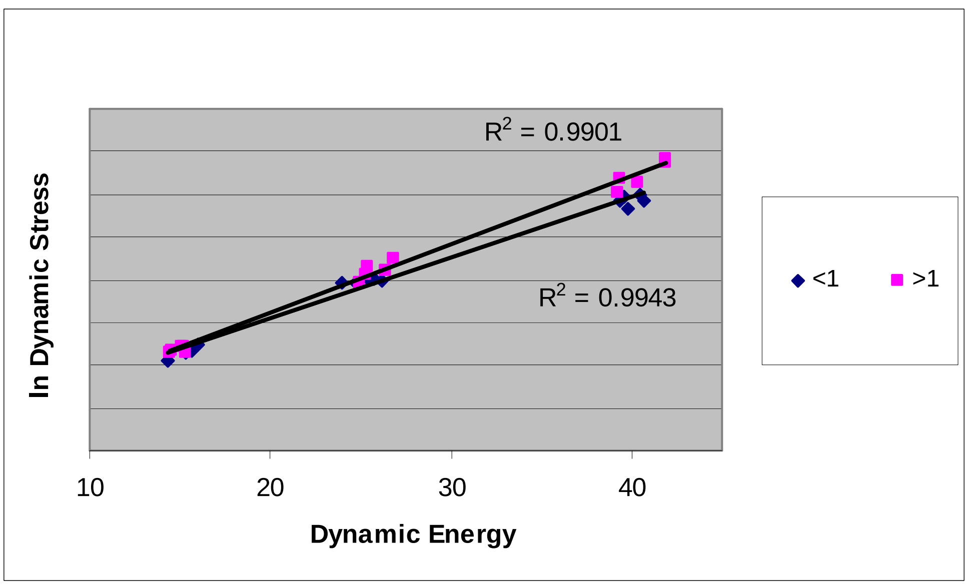


Figure 10: Linearized data for Arcel 1.5 pcf Drop 5 for less than and greater than 1 inch

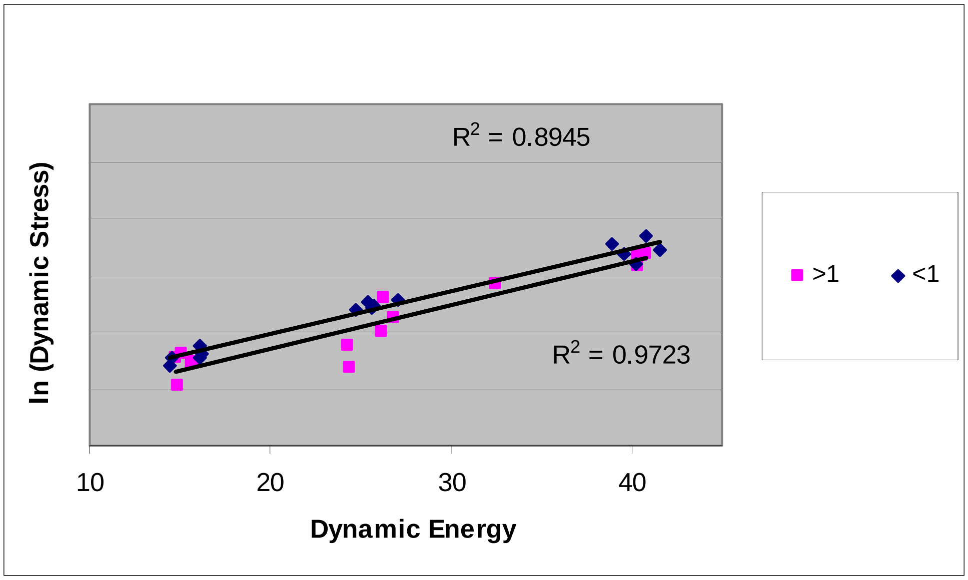


Figure 11: Linearized data for Arcel 1.9 pcf Drop 1 for less than and greater than 1 inch

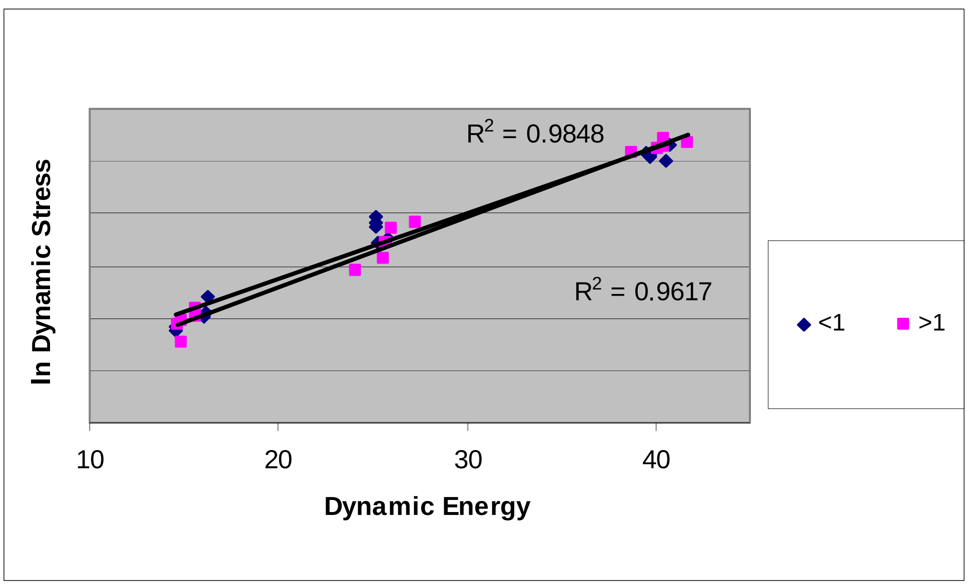


Figure 12: Linearized data for Arcel 1.9 pcf Drop 2 for less than and greater than 1 inch

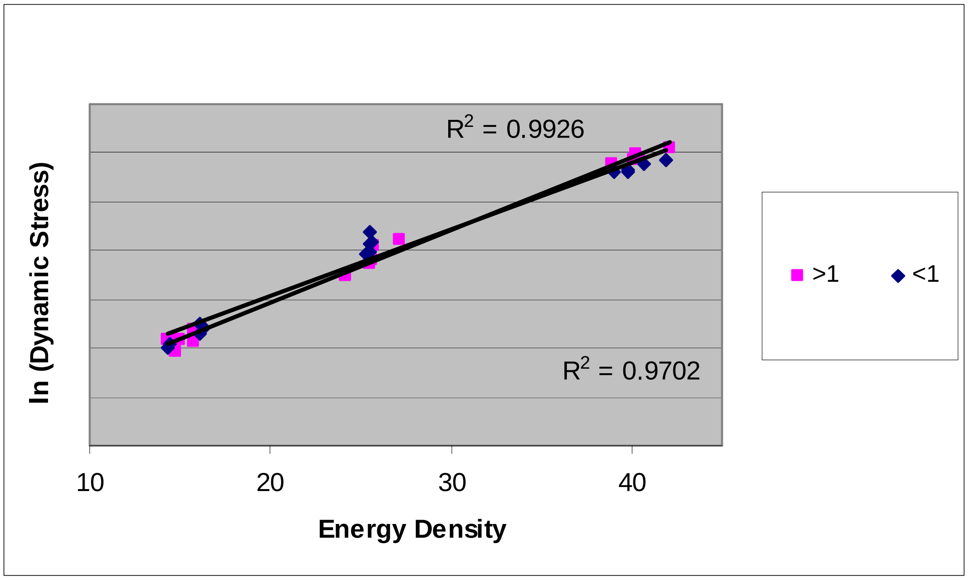


Figure 13: Linearized data for Arcel 1.9 pcf Drop 3 for less than and greater than 1 inch

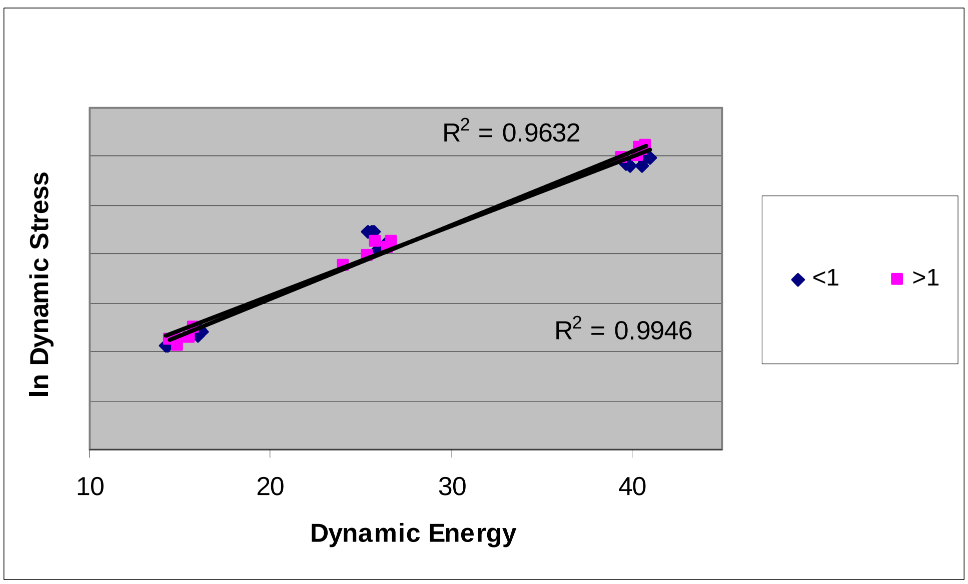


Figure 14: Linearized data for Arcel 1.9 pcf Drop 4 for less than and greater than 1 inch

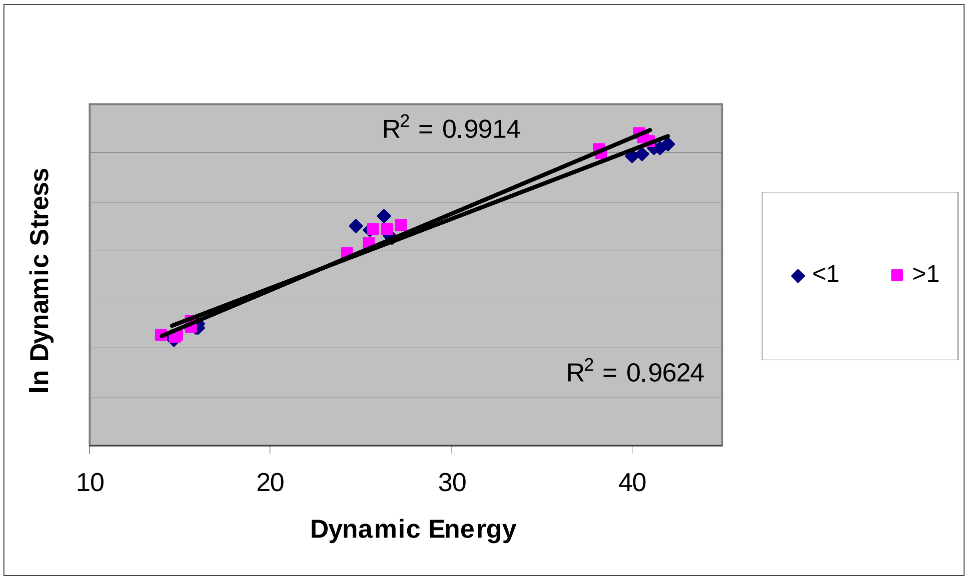


Figure 15: Linearized data for Arcel 1.9 pcf Drop 5 for less than and greater than 1 inch

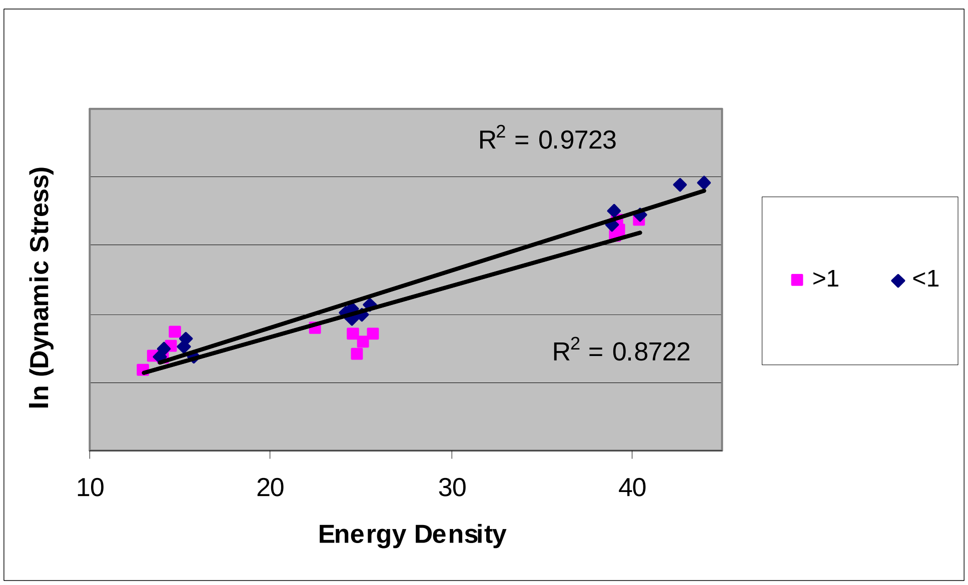


Figure 16: Linearized data for expanded polypropylene pcf Drop 1 for less than and greater than 1 inch

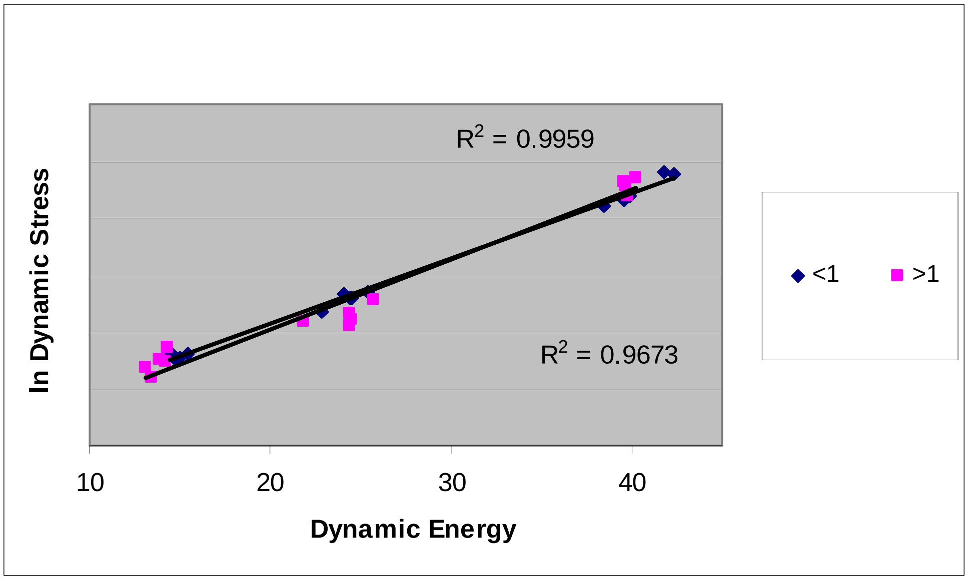


Figure 17: Linearized data for expanded polypropylene Drop 2 for less than and greater than 1 inch

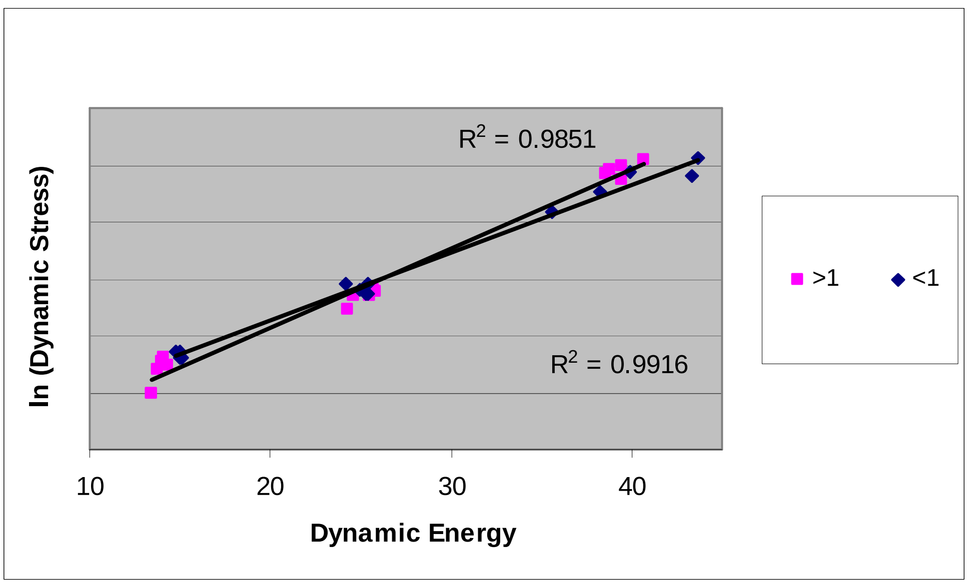


Figure 18: Linearized data for expanded polypropylene Drop 3 for less than and greater than 1 inch

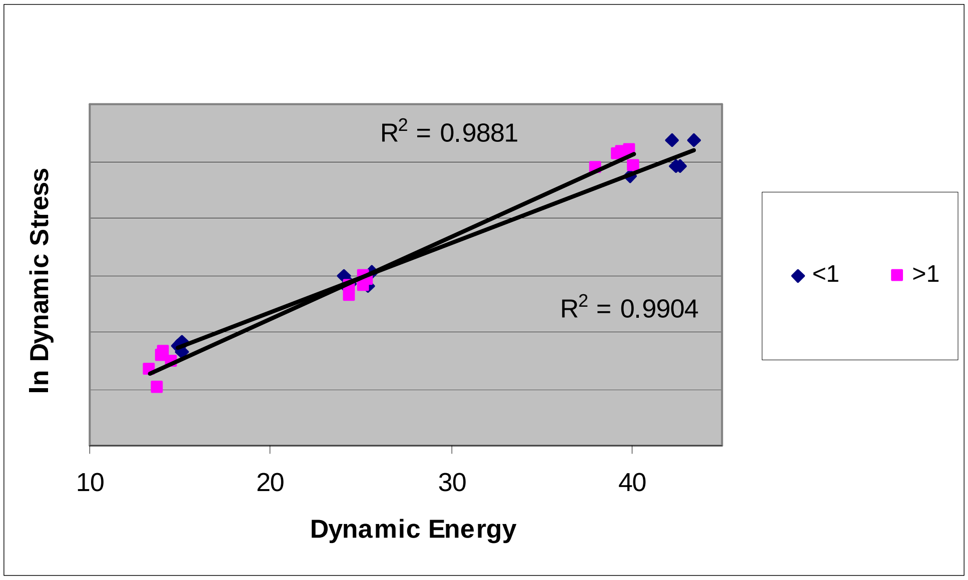


Figure 19: Linearized data for expanded polypropylene Drop 4 for less than and greater than 1 inch

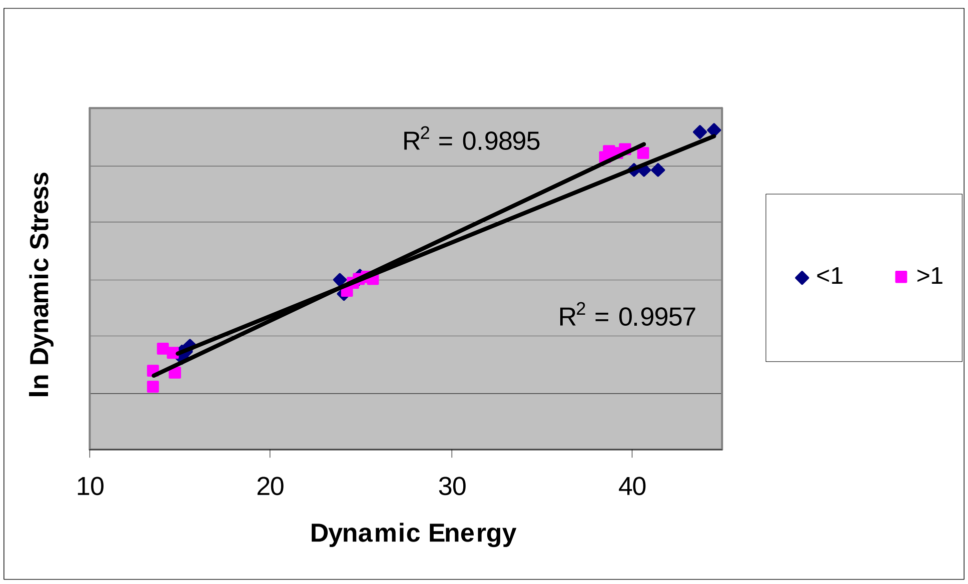


Figure 20: Linearized data for expanded polypropylene Drop 5 for less than and greater than 1 inch

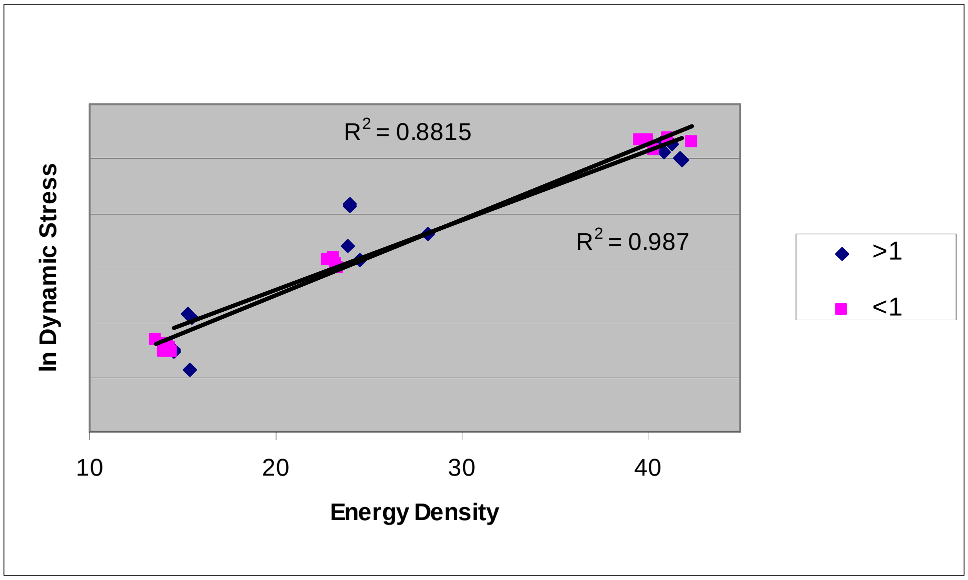


Figure 21: Linearized data for expanded polyethylene Drop 1 for less than and greater than 1 inch

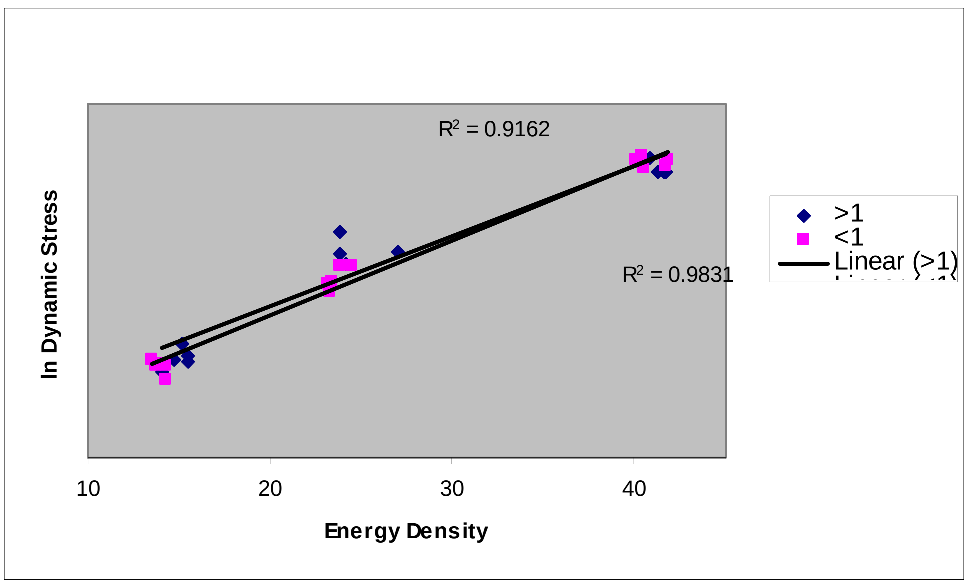


Figure 22: Linearized data for expanded polyethylene Drop 2 for less than and greater than 1 inch

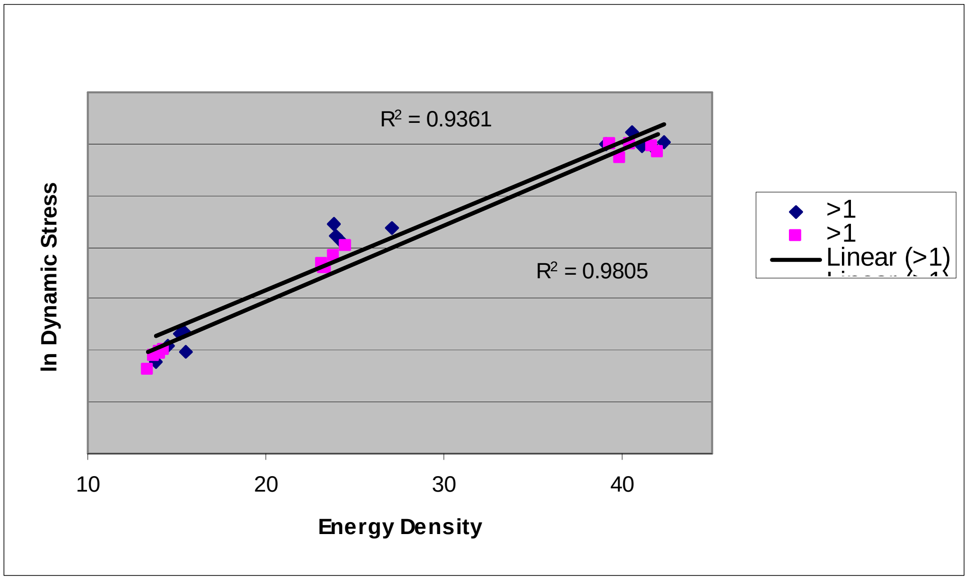


Figure 23: Linearized data for expanded polyethylene Drop 3 for less than and greater than 1 inch

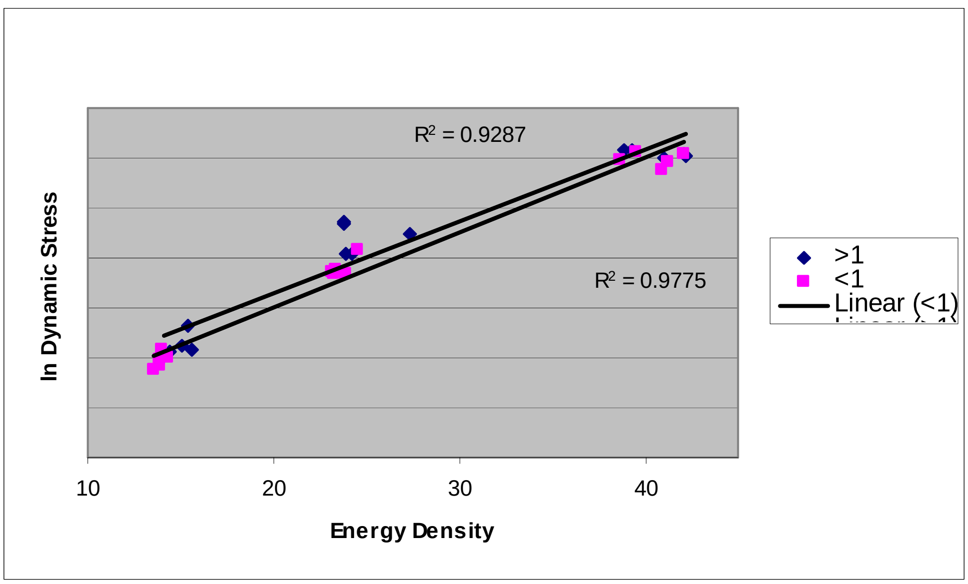


Figure 24: Linearized data for expanded polyethylene Drop 4 for less than and greater than 1 inch

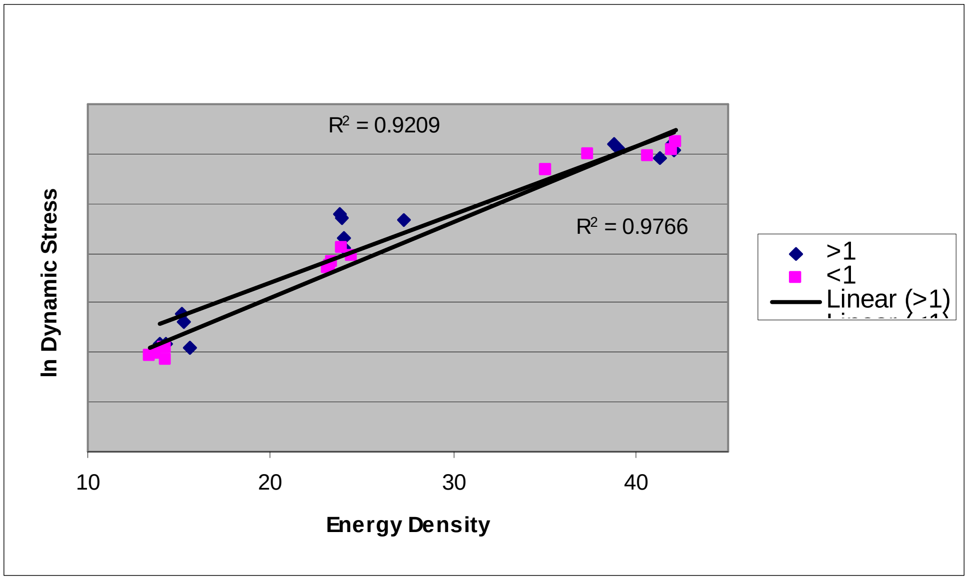


Figure 25: Linearized data for expanded polyethylene Drop 5 for less than and greater than 1 inch

APPENDIX C:

Raw data used in comparisons for Method III

Arcel 1.3 Raw Data					
Static Load (lb/in²)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference (g)
Energy Level 15 (in-lb/lb³)					
0.41	18.16	0.49	95.76	81.85	13.90
0.41	18.12	0.49	126.12	128.46	-2.34
0.41	18.23	0.49	149.57	146.81	2.75
0.41	18.21	0.49	146.36	164.08	-17.72
0.41	18.31	0.49	152.86	169.25	-16.39
0.41	26.84	0.71	92.93	83.43	9.49
0.41	26.8	0.71	124.5	131.53	-7.03
0.41	26.76	0.71	140.96	150.69	-9.73
0.41	26.87	0.71	149.99	168.21	-18.22
0.41	26.88	0.71	161.75	173.50	-11.75
Energy Level 25 (in-lb/lb³)					
1.04	12.26	0.49	70.88	59.25	11.62
1.04	12.17	0.49	122.03	105.41	16.61
1.04	12.16	0.49	135.46	130.09	5.36
1.04	12.64	0.49	144.84	151.21	-6.37
1.04	12.92	0.49	166.73	163.15	3.57
1.04	18.44	0.73	66.33	64.52	1.80
1.04	18.67	0.73	112.61	118.57	-5.96
1.04	18.64	0.73	141.76	148.18	-6.42
1.04	18.05	0.73	132.4	158.46	-26.06
1.04	18.22	0.73	164.09	163.28	0.80
Energy Level 40 (in-lb/lb³)					
1.52	19.65	0.7	106.51	113.39	-6.88
1.52	20.02	0.7	219.52	272.47	-52.95
1.52	19.67	0.7	250.86	361.49	-110.63
1.52	20.12	0.7	263.58	394.43	-130.85
1.52	20.08	0.7	282.07	399.08	-117.01
1.52	12.8	0.48	97.71	99.88	-2.17
1.52	12.87	0.48	188.59	219.72	-31.13
1.52	12.85	0.48	224.03	304.04	-80.01
1.52	12.99	0.48	245.5	309.16	-63.66
1.52	13.12	0.48	255.95	318.18	-62.23

Figure 1: Raw data for Arcel 1.3 lb/ft³

Arcel 1.5 Raw Data					
Static Load (lb/in^2)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference (g)
Energy Level 15 ($in\text{-}lb/lb^3$)					
0.41	18.46	0.51	95.57	85.95	9.61
0.41	17.94	0.51	121.6	116.44	5.15
0.41	17.07	0.51	124.32	111.14	13.17
0.41	17.93	0.51	147.72	150.05	-2.33
0.41	18.59	0.51	151.61	162.63	-11.02
0.41	26.3	0.75	87.99	83.91	4.07
0.41	24.99	0.75	108.2	110.50	-2.30
0.41	26.98	0.75	139.21	142.05	-2.84
0.41	26.75	0.75	147.46	153.74	-6.28
0.41	26.52	0.75	153.26	156.83	-3.57
Energy Level 25 ($in\text{-}lb/lb^3$)					
1.04	17.4	0.78	55.08	50.69	4.38
1.04	17.5	0.78	94.01	86.02	7.98
1.04	17.47	0.78	110.58	105.56	5.01
1.04	17.36	0.78	127.48	115.25	12.23
1.04	17.4	0.78	134.23	120.54	13.68
1.04	12.28	0.5	61.08	56.26	4.81
1.04	11.24	0.5	98.7	106.32	-7.62
1.04	11.98	0.5	121.71	120.41	1.29
1.04	12.06	0.5	132.85	131.71	1.13
1.04	12.13	0.5	137.19	142.47	-5.28
Energy Level 40 ($in\text{-}lb/lb^3$)					
1.52	20.21	0.74	90.25	80.04	10.20
1.52	20.29	0.74	172.24	202.59	-30.35
1.52	20.37	0.74	210.05	158.43	51.61
1.52	20.08	0.74	211.58	283.70	-72.12
1.52	20.14	0.74	257.4	304.16	-46.76
1.52	13.33	0.48	103.41	82.29	21.11
1.52	13.4	0.48	198.68	208.78	-10.10
1.52	13.38	0.48	237.39	271.85	-34.46
1.52	13.37	0.48	260.59	302.24	-41.65
1.52	13.38	0.48	276.44	321.37	-44.93

Figure 2: Raw data for Arcel 1.5 lb/ft^3

Arcel 1.9 Raw Data					
Static Load (lb/in²)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference (g)
Energy Level 15 (in-lb/lb³)					
0.41	25.92	0.75	104.33	92.72	11.60
0.41	25.92	0.75	120.59	120.81	-0.22
0.41	25.53	0.75	131.27	135.01	-3.74
0.41	25.59	0.75	140	145.14	-5.14
0.41	26.05	0.75	148.88	153.97	-5.09
0.41	18.12	0.48	113.29	97.31	15.97
0.41	18.1	0.48	130.9	131.49	-0.59
0.41	18.07	0.48	147.09	150.74	-3.65
0.41	17.98	0.48	150.45	160.29	-9.84
0.41	17.88	0.48	157.77	167.59	-9.82
Energy Level 25 (in-lb/lb³)					
1.04	17.69	0.75	62.68	53.93	8.74
1.04	18.01	0.75	123.69	95.85	27.83
1.04	18.32	0.75	154.35	120.48	33.86
1.04	18.16	0.75	178.48	129.76	48.71
1.04	18.73	0.75	201.4	146.60	54.79
1.04	12.86	0.5	69.26	58.49	10.76
1.04	12.3	0.5	111.19	99.80	11.38
1.04	12.04	0.5	135.08	116.96	18.11
1.04	12.59	0.5	158.32	139.22	19.09
1.04	12.73	0.5	161.03	148.90	12.12
Energy Level 40 (in-lb/lb³)					
1.52	20.67	0.75	74.33	71.09	3.23
1.52	19.78	0.75	167.83	182.58	-14.75
1.52	19.81	0.75	223.96	248.50	-24.54
1.52	19.76	0.75	250.94	274.89	-23.95
1.52	20.69	0.75	279.19	348.95	-69.76
1.52	12.9	0.5	77.77	64.11	13.65
1.52	13.12	0.5	177.22	178.93	-1.71
1.52	12.95	0.5	222.03	232.42	-10.39
1.52	13.46	0.5	243.7	287.61	-43.91
1.52	13.45	0.5	262.41	317.92	-55.51

Figure 3: Raw data for Arcel 1.9 lb/ft³

EPE Raw Data					
Static Load (lb/in²)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference (g)
Energy Level 15 (in-lb/lb³)					
0.41	25.21	0.82	104.99	113.93	-8.94
0.41	25.07	0.82	120.18	132.31	-12.13
0.41	24.75	0.82	103.35	138.12	-34.77
0.41	25.11	0.82	108.87	148.50	-39.63
0.41	24.87	0.82	119.15	159.67	-40.52
0.41	16.31	0.5	103.65	119.41	-15.76
0.41	16.35	0.5	113.48	139.82	-26.34
0.41	16.06	0.5	122.13	145.55	-23.42
0.41	15.99	0.5	135.88	154.54	-18.66
0.41	16.2	0.5	129.81	168.93	-39.12
Energy Level 25 (in-lb/lb³)					
1.04	18.12	0.82	88.42	84.43	3.98
1.04	18.12	0.82	98.82	104.77	-5.95
1.04	18.05	0.82	120.15	113.82	6.32
1.04	18.15	0.82	121.28	120.40	0.87
1.04	18.11	0.82	125.14	127.28	-2.14
1.04	12.65	0.59	90.38	81.02	9.35
1.04	13.2	0.59	126.96	106.79	20.16
1.04	13.18	0.59	127.86	116.10	11.75
1.04	13.24	0.59	118.13	122.80	-4.67
1.04	13.2	0.59	147.81	129.74	18.06
Energy Level 40 (in-lb/lb³)					
1.52	21.55	0.82	191.42	172.57	18.84
1.52	21.96	0.83	259.8	254.24	5.55
1.52	21.99	0.83	262.69	291.00	-28.31
1.52	21.48	0.83	280.11	287.81	-7.70
1.52	20.32	0.83	264.33	248.33	15.99
1.52	16.64	0.6	186.45	190.75	-4.30
1.52	16.37	0.6	237.67	254.40	-16.73
1.52	16.35	0.6	255.73	291.19	-35.46
1.52	16.53	0.6	274.68	316.90	-42.22
1.52	16.54	0.6	294.92	319.97	-25.05

Figure 4: Raw data for Expanded Polyethylene 1.9 lb/ft³

EPP Raw Data					
Static Load (lb/in²)	Drop Height (in)	Thickness (in)	Acceleration (g)	Predicted Value (g)	Difference (g)
Energy Level 15 (in-lb/lb³)					
0.41	27.61	0.75	103.25	94.79	8.45
0.41	27.07	0.75	104.64	98.69	5.94
0.41	26.98	0.75	113.21	99.38	13.82
0.41	27.33	0.75	110.77	103.12	7.64
0.41	27.36	0.75	113.67	104.47	9.19
0.41	19.25	0.51	95.73	96.00	-0.27
0.41	17.98	0.51	103.07	96.99	6.07
0.41	18.41	0.51	106.81	99.60	7.20
0.41	18.28	0.51	114.52	101.59	12.92
0.41	18.17	0.51	111.65	102.27	9.37
Energy Level 25 (in-lb/lb³)					0
1.04	17.39	0.74	50.94	52.37	-1.43
1.04	17.33	0.74	71.1	68.51	2.58
1.04	17.94	0.74	76.15	78.57	-2.42
1.04	17.21	0.74	78.35	77.07	1.27
1.04	18.12	0.74	86.54	87.28	-0.74
1.04	12.05	0.52	53.47	54.00	-0.53
1.04	11.85	0.52	72.06	70.31	1.74
1.04	11.89	0.52	80.8	76.47	4.32
1.04	11.81	0.52	83.93	79.08	4.84
1.04	11.74	0.52	84.07	80.66	3.40
Energy Level 40 (in-lb/lb³)					0
1.52	19.23	0.75	75.75	61.14	14.60
1.52	19.5	0.75	114.13	119.19	-5.06
1.52	21.31	0.75	145.48	188.66	-43.18
1.52	20.88	0.75	154.37	195.47	-41.10
1.52	19.77	0.75	153.64	179.49	-25.85
1.52	13.58	0.48	91.81	71.08	20.72
1.52	13.09	0.48	141.02	133.99	7.02
1.52	13.49	0.48	166.84	182.92	-16.08
1.52	13.41	0.48	190.87	196.97	-6.10
1.52	13.77	0.48	213.09	233.31	-20.22

Figure 5: Raw data for expanded polypropylene 1.9 lb/ft³

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